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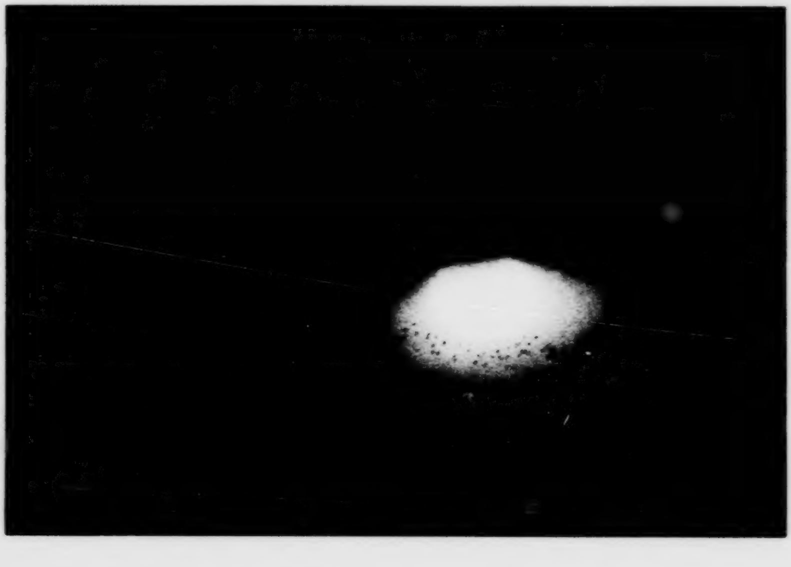
Alternative Energy Technology in Canada

NRC's Energy R&D Program 1975–1985

September 1986



Canada

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National Research Council of Canada
Division of Energy

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PROLOGUE

The 1973 Arab Oil Embargo is today a distant memory for most Canadians, despite the tremendous economic havoc it wrought on the industrialized world. The price of oil, as these words were being written, is under $20 a barrel and not $60, or even $100, as knowledgeable economists and energy specialists had speculated during the peak of the crisis.

While television newscasts no longer feature lineups at gasoline pumps, concentrating instead on reports of the economic turmoil and devastation that low oil prices are causing, no prudent person can be complacent about future energy supplies. Whether we are consuming cheap oil or expensive oil, we are still running out of it and, sooner or later, this will be reflected in price and availability. Conservation and alternative energy sources remain vitally important to Canada's long-term economic future.

This report focuses on the status of alternative energy technology. More specifically, it deals with the portion of the federal government's program of energy research and development that was coordinated by the National Research Council's Division of Energy. Ambitious in scope, this program encompassed R&D activities in solar, wind, bioenergy, peat, heat pumps, hydrogen and energy storage systems, and nuclear fusion.

While the report is essentially a technical overview of the Canadian alternative energy program, it does highlight key international developments as well. Against this background, Canadian achievements in alternative energy are demonstrably significant in both number and caliber.

Most of this program's research and development was conducted extramurally, under NRC supervision, by industrial organizations, university researchers, engineering companies, consultants, and a variety of other scientific and technical institutions. The National Research Council has a long tradition of technical collaboration with industry and other partners, and many of these cooperative undertakings have already resulted in commercial payoff. Dozens of companies have developed products and services related to alternative energy and are now selling them here and abroad.

By the same token, modest in-house energy research done in various NRC laboratories collaborating with the Division of Energy not only explored new areas of science (to provide the basis for better technology), but also made available an objective core of specialists for appraising the scientific and technical merits of energy R&D options. This significantly enhanced the relevance of several programs.

As of late 1986, NRC's Division of Energy has been phased out, but some of the research it initiated will be continued by other government agencies and departments. It is worth noting that renewable energy — not counting the large contribution of hydroelectric power — now accounts for nearly 6% of Canada's domestic energy production, more than double the 1974 figure.

This report documents the current technical status of alternative energy technologies and what will be required — when economic and policy considerations so demand — to achieve further deployment and commercialization of alternative energy systems. Canada will be well served if such R&D is continued, even if at a slower pace than during the past decade.

It has been a privilege to lead the dedicated NRC teams, and their many collaborators, in the programs described below. Their work has been characterized by vigour, innovation, and technical integrity in the best research traditions.

It is also a pleasure to acknowledge the diligent work of Robert Stecklasa, who developed the text and figures for this report, in ongoing consultation with the specialists in the several program areas.

E.P. Cockshutt
Director
Division of Energy
1986

1 BACKGROUND

Development of the Alternative Energy Program

At the start of the 1970s, only a small number of researchers and entrepreneurs were seeking to produce economical energy from solar collectors, wind turbines, wood gasifiers, and other alternative energy technologies. Although the long-range nuclear fusion option stood out as an exception and was receiving substantial R&D funding in some countries, this was not the case in Canada.

The 1973 Arab Oil Embargo, however, caused a sudden increase in the price of energy and, among industrialized nations, triggered a complete reexamination of energy production and consumption, including the role of alternative energy technologies. For a northern nation such as Canada, the world's heaviest consumer of energy on a per capita basis, the prospects of scarce high-priced oil were sobering to consider.

The implications of expensive energy were made strikingly clear in a major policy study produced by the Department of Energy, Mines and Resources (EMR) in 1973. The "Standard Forecast" (as the study came to be known) projected that primary energy consumption would reach 14 EJ by 1984, almost double the 1973 consumption. Moreover, it projected a further doubling of energy consumption between 1984 and the turn of the century. The study, which forecast future energy demand by extrapolating energy-related data from the previous 15 years, assumed continued growth in population and per capita consumption.

As more detailed information continued to be gathered about future energy supplies, the federal government realized that achieving energy self-sufficiency and averting an economically and socially crippling energy crisis posed numerous policy, technical, and economic challenges. *Energy Strategy* *for Canada*, a 1976 report that established the supply/demand projection for each major energy commodity, reflected this grave concern over the supply of energy. In particular, it forecast a serious and steadily worsening shortfall in domestic crude oil supplies. According to this report, the demand for oil could — by 1985 — exceed domestic supply by one million barrels per day. This report and others also confirmed that no single measure could lead to energy self-sufficiency, at least with respect to oil. A successful energy policy would encourage a variety of energy options, including measures to promote conservation, exploitation of oil sands, substitution of oil with other fuels, and, of course, the development of alternative energy sources.

Such options formed the federal government's constantly evolving energy policy of the 1970s and 1980s. Many of them — including the development of alternative energy technologies — would require a large investment in research and development.

Some of the main federal government energy programs of the 1970s and '80s

- Canadian Home Insulation Program (CHIP)
- Measures for Energy Conservation in New Buildings
- Automotive Fuel Consumption Standards
- Federal Internal Energy Conservation Program
- Forest Industry Renewable Energy Program
- Purchase and Use of Solar Heating
- Canadian Oil Substitution Program (COSP)
- Gas Pipeline Extension
- Propane/Natural Gas Automotive Conversions
- Canada Lands Oil & Gas Act
- Energy Demonstration Program

The threat of oil shortages prompted the federal government to sponsor a variety of programs aimed at reducing consumption and encouraging the use of new energy sources in all sectors of the economy.

The Panel on Energy Research and Development

With the price of oil escalating rapidly in the early 1970s and with Canadians becoming increasingly concerned about the supply of gasoline and heating oil, the federal government turned its attention to the alternatives to oil. In late 1973, Cabinet instructed the Department of Energy, Mines and Resources to convene an interdepartmental Task Force on Energy Research and Development. Its first meeting, held in January 1974, was attended by the Deputy Ministers of all departments and agencies concerned with energy research.

Members of the Task Force made some significant decisions that established the pattern for the federal government's emerging energy R&D program. Specifically, they rejected the formation of a new single agency to perform or direct all federal energy research, reasoning that this would cause unacceptable delays and expensive duplication of staff and facilities. Instead, they favoured a mechanism for coordinating the energy-related research that various departments and agencies were already carrying out or might appropriately undertake.

In addition, the Task Force members decided to review existing energy research and development before soliciting new funding from the government. The Task Force assembled a Working Committee from within the ranks of its member departments to direct the review, formulate recommendations for new research, and set priorities. At the same time, it set up the Office of Energy Research and Development (OERD) within EMR to provide secretariat support to these operations.

The Task Force essentially completed its work when it presented its report to Cabinet, and subsequently published *Science and Technology for Canada's Energy Needs* in April 1975. This report enunciated the goal of the federal research and development program, which was:

> *to develop the scientific and technical capabilities to achieve self-reliance in energy with minimal environmental, social or economic costs and maximum industrial or quality of life advantages.*

To ensure a balanced coverage of technical areas, including those related to alternative energy technologies, the report outlined a system of tasks and programs and designated lead departments to manage them. Specifically, more than 30 individual programs were identified and grouped under the major tasks, namely conservation, fossil fuels, nuclear energy, renewable energy, and energy transportation. Some revisions in the task structure occurred subsequently, but the basic framework remained essentially unchanged.

The Task Force members also decided to replace the Working Committee with a permanent Panel on Energy Research and Development (PERD). The duties of this panel, which held its first meeting in July 1975, included reviewing and assessing federal energy R&D, coordinating this R&D with energy policy, and preparing recommendations for allocating funds.

The Panel on Energy Research and Development wielded considerable

Framework for the federal government's energy research and development programs (1983)

Task 1: Energy Conservation

- Industrial Energy Research and Development Program
- Agri-food
- Buildings
- Transportation sector
- Demand (analysis of conservation initiatives, energy consumption, conservation behaviour)
- Energy systems (includes such activities as cogeneration, district heating, energy from wastes)

Task 2: Oil Sands, Heavy Oil, and Coal

- Bitumen and heavy oil recovery
- Oil sands / and heavy oil (improved technologies for production of synthetic fuels)
- Coal supply
- Coal combustion
- Environment

Task 3: Nuclear Energy

- Fuel resource base
- Fusion

Task 4: Renewable Energy

- Hydraulics (includes ocean energy and small-scale hydro)
- Solar
- Bioenergy
- Wind
- Geothermal
- Peat

Task 5: New Liquid Fuels

- Direct liquefaction
- Gasification (coal and biomass)
- Biological processes (conversion of biomass into liquid fuels)
- Fuel processing (includes upgrading synthetic crude to high-quality transportation fuels and conversion of natural gas to distillate liquids)
- Fuel use (includes vehicle systems technology, fuel handling and dispensing systems, policy related techno-economic assessments)
- Hydrogen and energy storage
- Environment

Task 6: Conventional Energy Systems (oil, gas, electricity)

- Geoscientific R&D
- Marine engineering
- Offshore geotechnics
- Enhanced recovery
- Materials R&D for offshore structures
- Transportation of oil and gas
- Environment
- Electrical R&D

In 1975, an interdepartmental Task Force on Energy Research and Development outlined a system of tasks and programs that would encourage development of new and improved energy technologies and eventually help Canada to reach energy self-reliance. This system was implemented and, by 1983, federally funded energy R&D was divided into six major tasks comprising more than 30 programs.

influence. During the ensuing five years, it developed and consolidated the interdepartmental energy program, which heavily emphasized R&D in renewables and conservation. Although government departments like EMR and Atomic Energy of Canada Limited (AECL) continued to receive funding for pre-existing energy research as part of their ongoing departmental operations — referred to as A-base funding — the Panel on Energy Research and Development coordinated the spending of all additional federal government dollars committed to energy R&D.

In 1980, responding to another round of oil price increases, the government funded a significant number of additional energy R&D initiatives as part of its National Energy Program (NEP), and placed the Panel of Energy Research and Development in charge of developing them (see Figure 1). This

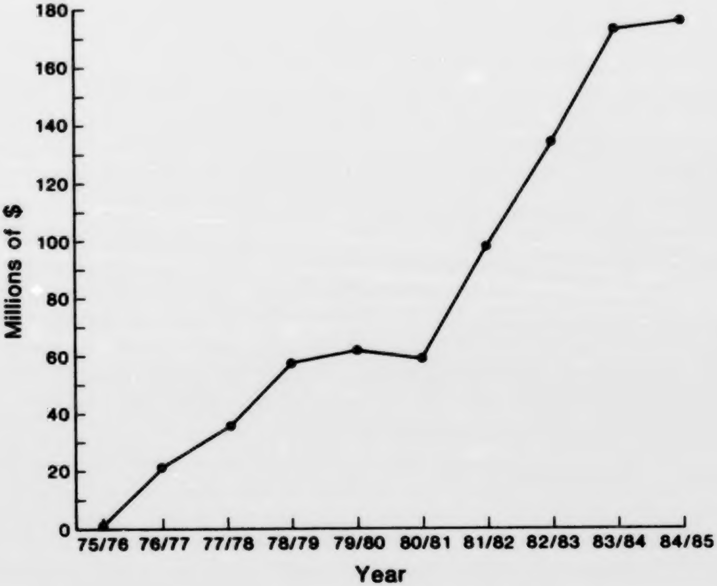


Figure 1 Annual allocation of funds by the Panel on Energy Research and Development

During the first years, the growth of funding under PERD reached a plateau of about $55 million (converted to 1984/85 dollars). A second major increase in the price of oil in 1979 and the subsequent introduction of the National Energy Program caused PERD funding to increase three-fold in real terms during the next several years.

expanded energy research program focused on alternative liquid fuels, efficient use of energy, new energy sources, and frontier resource technology.

In performing its duties, the Panel on Energy Research and Development developed a network of program committees representing involved departments and scientific and technical specialists. They evaluated funding and technical priorities within each of the more than 30 programs. This arrangement prevailed until the government decided, late in 1984, to reduce the scale and nature of the federal energy research and development activity.

Table 1. Allocation of PERD funding between 1975/76 and 1984/85

	$\$(\times 10^6)$
Renewables	Total: 199.3
Bioenergy	69.9
Wind	32.4
Hydraulic	5.4
Solar	80.6
Other	11.0
Energy conservation	Total: 142.3
Agrifood	11.9
Buildings	44.2
Industry	58.3
Transportation	27.9
Alternative fuels for transportation	85.3
Oil and gas	85.1
Oil sands and heavy oil	31.8
Coal	54.2
Electricity (including fusion and hydrogen)	75.9
Total	673.9

Conservation and renewable energy received more than half the energy funds distributed by the federal government's Panel on Energy Research and Development.

Financially, the Panel on Energy Research and Development gave alternative energy and conservation R&D a major impetus, although not nearly as large as that provided to the nuclear fission program during a period of several decades. As Table 1 shows, the federal government allocated $674 million to energy R&D programs coordinated by the Panel on Energy Research and Development. More than $340 million supported renewable and conservation research programs. The National Research Council (NRC) was responsible for much of this spending on renewable energy and conservation of energy.

National Research Council Role and Mandate in Energy Research and Development

As Canada's largest general-purpose research and development establishment, the National Research Council has for decades conducted research and development in a wide range of scientific and engineering disciplines. Thus, the major role it played in the federal energy research and development program is not surprising. In many cases NRC was the only establishment in the country with research capabilities in the new energy-related fields.

Talks between the President of NRC and the Deputy Minister of the Department of Energy, Mines and Resources had determined early on that NRC's established and potential strengths in conservation and new energy technologies could complement EMR's significant capabilities in fossil fuel research, as well as Atomic Energy of Canada Limited's expertise in nuclear fission. For this reason, the NRC played a key role in planning and operating the interdepartmental energy research and development program.

The National Research Council, in fact, had already made an extensive survey of its energy-related R&D activities as part of a 1972 study by the Science Council of Canada. This inventory of research and expertise permitted a rapid response and deployment of NRC specialists.

Within the first four months of 1974, NRC began coordinating the Renewable Energy task. It also took the lead role in reviewing the technologies and developing the research programs dealing with nuclear fusion, solar, wind energy, and energy conservation in commercial and residential buildings.

When the Panel on Energy Research and Development was formed one year later, NRC continued its responsibility for these programs. In addition, it agreed to assume the lead role for hydraulic/tidal energy and for transmission and distribution of electricity. Within a few years, heat pumps, hydrogen and energy storage systems, and peat were added to NRC's list of responsibilities.

More than 15 NRC directors and section heads participated in reviewing and developing the government's various energy R&D programs. The heavy involvement of seven of NRC's laboratory divisions in energy activities led to the development of a special mechanism for technical coordination. Accordingly, the position of Energy Project Coordinator was established in the summer of 1974 and filled (on a part-time basis) by the Section Head, Engine Laboratory, Division of Mechanical Engineering. With Cabinet endorsement of the Panel on Energy Research and Development's structure in 1975, the position of NRC Energy Project Coordinator became a full-time one. A Renewable Energy Task Coordinator was also appointed.

Originally, NRC had expected that all energy R&D would be performed or managed by the seven laboratory divisions involved. However, as the level of activity increased, and in particular as the volume of extramural research rapidly expanded, the Energy Project became a program branch in 1979 and a full-fledged division in 1981. By November 1984, the Division of Energy comprised a staff of 55, and managed an annual budget of $44 million (see Table 2).

Table 2. Division of Energy spending,
1980/81 – 84/85

Program	$\$(\times 10^{6})$
Solar	44
Nuclear fusion	23.7
Wind	20
Hydrogen and energy storage	18.9
Bioenergy	7.7*
Heat pumps	4.8
Peat	3.2

* The federal government's total expenditure on bioenergy was approximately triple NRC's budget since major bioenergy programs were also supported by the Canadian Forestry Service, Agriculture Canada, and Department of Energy, Mines and Resources.

NRC's Division of Energy directed the spending of more than $100 million on alternative energy research during its last four years of operation.

Overall, the National Research Council's role in energy-related research and development was much broader than that specifically managed by the Division of Energy. More than 40 NRC staff members in other divisions received about $12 million annually from the Panel on Energy Research and Development. Funding from NRC's internal operating budget provided a like amount for energy research.

Research and Development Involvement of Industry

From its beginnings, the federal energy R&D program deliberately involved many private sector firms and other organizations. This flowed from the government's "make-or-buy" policy, which scrutinized research activities within government and determined whether it was more appropriate to perform the research within government laboratories ("make") or contract the research out to industrial or institutional laboratories ("buy").

Implemented in the early 1970s, the policy favoured the "buy" route for near-term research and product development, with the compelling argument that technology transfer to industry is best effected by having the technology developed by industry's own research teams.

This policy, however, had broader implications. It required the same analysis of longer-term research projects, where linkages to industrial activity were less immediate. The government, in encouraging the "buy" route, awarded its departments and agencies substantial financial support to fund energy R&D, but allowed the size of their research groups to increase only minimally, thereby ensuring that the R&D was contracted out.

One of the most important spin-off benefits, from an R&D management point of view, was the experience and expertise gained in directing extramural research and combining this with an appropriate blend of in-house research activities.

Environmental Concerns

The federal government's energy R&D program acknowledged the environmental concerns of energy development. There existed (and still exists) an unease with respect to nuclear energy and its environmental effects among many Canadians; there was also the realization that conventional energy, both in its production and in its use, constitutes a large-scale burden on the environment. For these reasons, environmental aspects were identified as a major component of each energy program; particular emphasis was placed on alternative energy forms because of their minimal and dispersed environmental impacts.

International Collaboration

The era of cheap, secure oil supplies ended so quickly that an orderly transfer to other energy sources had no chance to occur. Industrial nations, mindful that billions of dollars would have to be invested in new energy systems, were generally willing to pool their efforts to spread the risk and cost of developing new energy technologies. The federal government's energy R&D program developed crucial links with other national and international research organizations.

The most important international collaboration occurred through the International Energy Agency (IEA), which represents a group of about 20 Western-bloc countries with membership in the Organization for Economic Cooperation and Development (OECD). The IEA, as one of its four primary activities, established a Committee for Research and Development, which in turn put in place a number of specific collaborative Implementing Agreements.

Typically, these agreements involved sharing R&D activities among 5 to 15 IEA countries, in relevant technical areas. In some instances, work was "task shared," that is, each country performed work relative to agreed objectives and then shared the results with the other participating countries. In other instances, work was "cost shared," with each country making a financial contribution towards a mutually defined research program. These IEA agreements fostered a sizeable information network that dealt with many aspects of energy development and application and significantly enriched the Canadian effort. They also opened the door for bilateral and multilateral exchanges, in areas complementary to IEA tasks.

Collaboration with Universities

Another important collaborative effort involved the Natural Sciences and Engineering Research Council's (NSERC) Strategic Grant Program for universities. Created in 1979 to address key technologies, including energy, this mechanism encouraged university researchers to submit proposals for multi-year research projects that met Canadian needs and priorities.

A number of projects, particularly relevant to longer term energy options such as fusion, photochemical conversion, and electrochemistry, received support under this program. They complemented the Panel on Energy Research and Development's contract research system and brought, through the eyes of university researchers, further valuable perspectives on Canadian energy research.

Energy Supply and Demand in Perspective

As noted previously, the federal government spent billions of dollars on a wide variety of programs to reduce oil consumption in Canadian homes and industry. This expenditure, along with the development of new energy technologies, substantially changed the energy supply/demand situation between 1974 and 1984.

The 1974 data, presented in Table 3, show domestic production at 8723 PJ and total end-use consumption of 5719 PJ. The population of Canada in 1974 was 22.4 million people. Corresponding data for 1984, presented in Table 4, show domestic production at 9609 PJ, along with a total consumption of 6158 PJ. The population had by then grown to 25.2 million, a 13% increase.

Comparison of these two energy "balance sheets" indicates the many important changes that transpired during this 10-year period. The data indicate the success of R&D and off-oil incentive programs, plus the powerful effects of rising prices. They also indicate where some of the future challenges still lie. Among the main observations:

- Domestic energy production increased 10% between 1974 and 1984, with large increases in coal, hydraulic, nuclear, and renewable energy offsetting a significant reduction in oil production. The renewable energy increase was due to major harnessing of wood wastes by the forest products industry and to the growing use of residential wood stoves. Even in 1984, however, more than a third of the domestic demand was supplied by oil.
- Net exports of energy commodities increased by 20% between 1974 and 1984, with all energy commodities being in surplus in 1984. Particularly important were increased exports of coal and electricity, as well as the fact that oil was again being exported.
- While most of the increased electricity supply came from hydroelectric and nuclear sources, thermal conversion from coal to electricity greatly increased; this was partially offset by less oil and gas conversion to electricity.
- The end-use demand for energy increased 8% from 1974 to 1984, but since this was accompanied by a 13% population increase, the per capita

Table 3. Energy supply and demand in Canada, 1974 (population: 22.4 million)

	PJ								
	Oil	Gas	Coal	Hydro	Nuclear	Renewable	Electricity	Steam	Totals
Domestic Production	4125	3043	526	769	40	220	—	—	8723
Net exports	261	1147	−88	—	—	—	47	—	1367
Conversion*	122	173	374	769	40		−1009	—	469
Losses, non-energy, etc.	673	418	−13	—	—	—	90	—	1168
End-use Demand	3069	1305	253	—	—	220	872	—	5719
Industry	554	626	242	—	—	180	425	—	2027
Transport	1599	—	3	—	—	—	—	—	1602
Buildings	916	679	8	—	—	40	447	—	2090

* Refers to the conversion of primary energy sources into secondary forms, mainly electricity.

Table 4. Energy supply and demand in Canada, 1984 (population: 25.2 million)

	PJ								
	Oil	Gas	Coal	Hydro	Nuclear	Renewable	Electricity	Steam	Totals
Domestic production	3431	3021	1396	1022	213	526	—	—	9609
Net exports	344	997	174	—	—	—	141	—	1656
Conversion	69	67	918	1022	213	23	−1532	−46	734
Losses, non-energy, etc.	562	310	66	—	—	—	113	—	1051
End-use Demand	2456	1647	238	—	—	503	1278	46	6168
Industry	319	695	234	—	—	401	577	46	2272
Transport	1492	13	—	—	—	—	9	—	1514
Buildings	645	939	4	—	—	102	692	—	2382

Renewable energy accounted for 3.5% of Canada's domestic energy production in 1974, vs. 47% for oil (see Table 3). By 1984, renewable energy accounted for 5.5% of Canada's domestic productions, vs. 35.7% for oil, more than double the 1974 contribution of 220 PJ (see Table 4).

use of energy actually decreased. Major increases in electricity, gas, and renewable energy use compensated for the reduced use of oil products.

- The industrial demand for energy just kept pace with the population growth between 1974 and 1984; increased electricity, gas, and renewables compensated for reduced oil use.
- In the transportation sector, the dependence on oil remained almost complete, but there was a decrease in demand notwithstanding the population increase. More energy-efficient road vehicles are seen as the prime reason for the reduced transportation demand, rather than any reduction in miles travelled.
- In the buildings sector, the demand increased but only in proportion to the population; major increases in gas and electricity usage compensated for the 30% reduction in oil use.

Considering the prime role of oil in the supply/demand balance, it is worth examining the projections contained in *An Energy Strategy for Canada*, published in 1976. As Figure 2 illustrates, demand was expected to

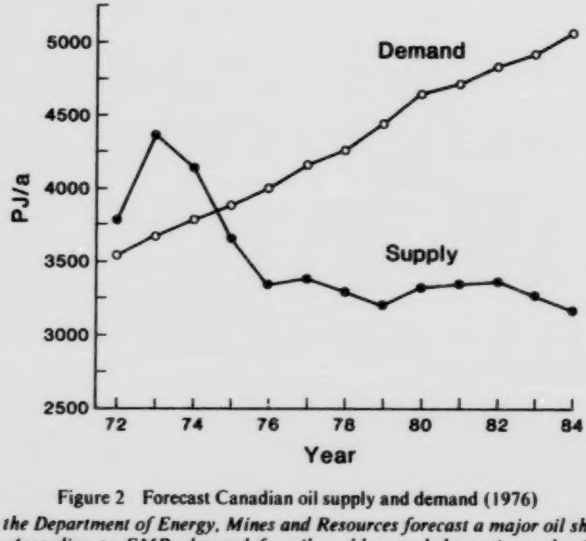


Figure 2 Forecast Canadian oil supply and demand (1976)

In 1976, the Department of Energy, Mines and Resources forecast a major oil shortage in Canada. According to EMR, demand for oil could exceed domestic production by as much as one million barrels of oil per day if the existing energy system and consumption patterns remained unchanged (see Figure 2). Significant changes did occur and, in 1983, Canada once again became a net oil exporter (see Figure 3).

rise continuously, while domestic supply was expected to decline steadily through to 1985. The shortfall between Canadian oil production and consumption was forecast to be more than 2000 PJ annually, in other words about one million barrels of oil daily.

Figure 3 shows what actually happened to oil supply and demand. With relatively minor fluctuations, domestic supply followed the 1976 forecast. Demand, however, did not rise steadily, but slowed through the late 1970s and then dropped rapidly in the early 1980s to values significantly below the forecast levels. The net result was an excess of supply, enabling Canada once again to become a net oil exporter.

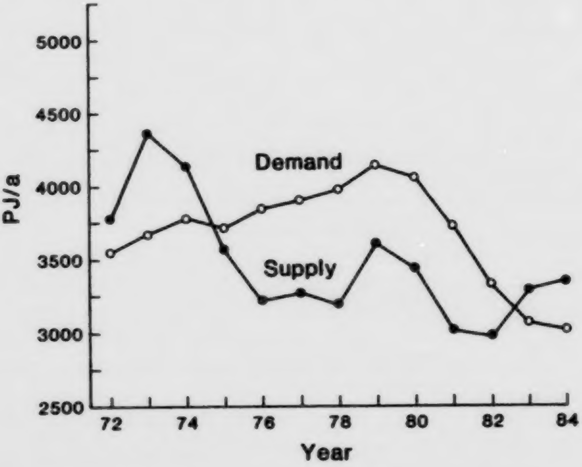


Figure 3 Actual Canadian oil supply and demand (1984)

These data clearly show that the combination of energy conservation and oil substitution measures provided impacts far more powerful than had been originally forecast in achieving energy self-reliance in Canada. The development of the alternative energy technologies described in the following chapters played a finite, if modest, role in the total scene, but these technologies will provide a much larger benefit when future energy dislocations inevitably occur.

2 SOLAR ENERGY

Description of Solar Energy Technology

The main challenge of solar energy technology is the economic exploitation of a large, but dilute, energy resource. The amount of solar radiation falling on 1 m^2 of rooftop in most Canadian cities is typically 4 to 5 GJ/a, comparable to much of Europe and the northern United States. Expressed another way, three days of average solar radiation on 1 m^2 of surface yields the energy equivalent of 1 L of oil.

Three distinct solar energy systems are readily available to capture radiation from the sun:

- Active solar heating systems generally consist of collectors for gathering the sun's energy, pumps and pipes for distributing heated fluids from the collector to a building, a heat storage reservoir, and electronic devices for controlling the operation of the system (see Figure 4).
- Photovoltaic systems consist of solar cells for converting the sun's radiation into electricity, batteries for storing electricity, and power conditioning units (see Figure 5). Solar cells are fabricated from a variety of semiconducting materials, although their efficiency varies in converting solar radiation into electricity. The materials used, in order of decreasing theoretical efficiency, include gallium arsenide (24%), indium phosphide (23%), cadmium telluride (21%), silicon (20%), gallium phosphide (17%), and cadmium sulfide (16%). Figure 6 illustrates the operation of a photovoltaic cell.
- Passive solar systems integrate the collection, distribution, and storage of energy into the design of the building itself to achieve economic reduction of energy consumption in buildings. As an example, the relatively inexpensive practice of orienting the windows of a conventional house to face

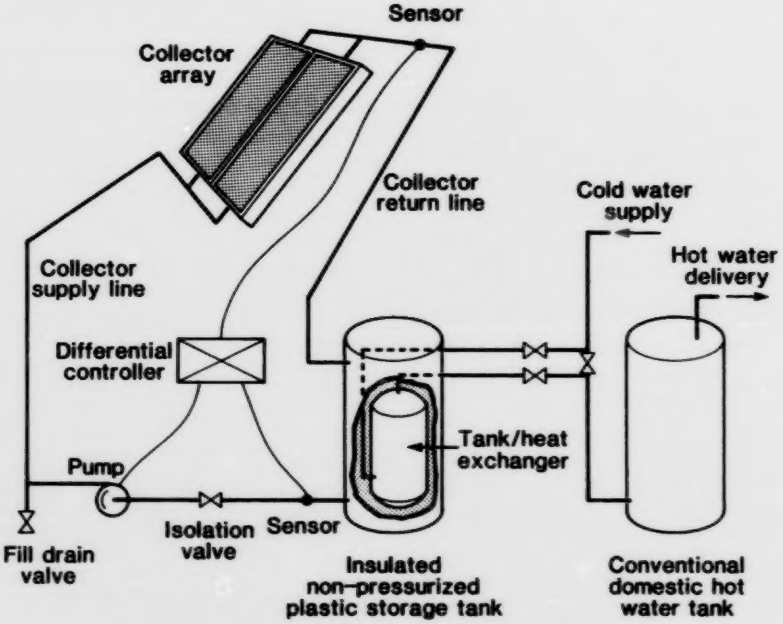

Sensor
Collector array
Collector return line
Cold water supply
Hot water delivery
Collector supply line
Differential controller
Tank/heat exchanger
Pump
Isolation valve
Sensor
Fill drain valve
Insulated non-pressurized plastic storage tank
Conventional domestic hot water tank

Figure 4 Main components of an active solar heating system

south can result in solar radiation contributing up to 25% of space heating needs. Masonry walls, slate floors, and stone fireplaces may be strategically placed to absorb solar energy during the day and help maintain a comfortable temperature during the night.

Program Rationale and Background

In the mid-1970s, many Canadians viewed the wide-scale implementation of solar energy as inevitable, a sentiment shared widely enough that it influenced the evolution of federal solar energy policies.

With energy prices on the rise, the Canadian consumer certainly had reason to learn more about the solar option. A Canadian family of four needs 15 to 20 GJ/a of energy for heating water and 40 to 120 GJ/a for space heating (a barrel of heavy crude oil has an energy content of 6.5 GJ).

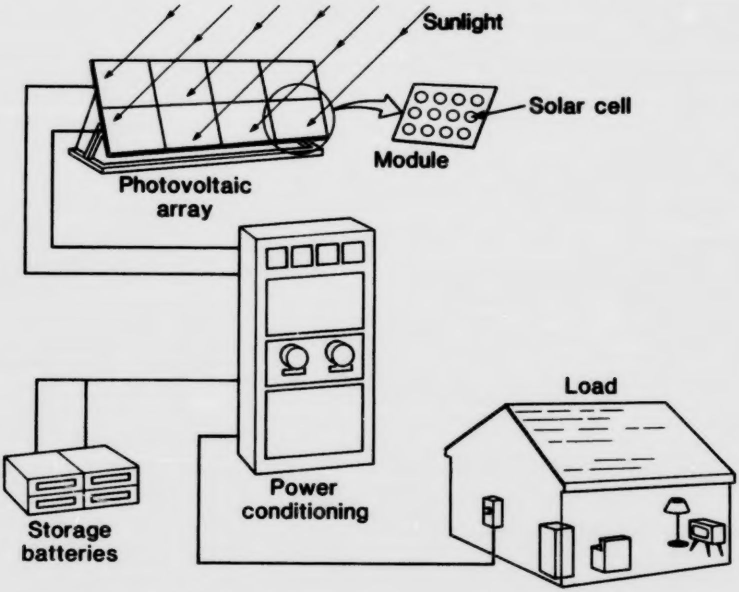


Figure 5 Main components of a photovoltaic system

Early federal government solar thrusts supported the development and implementation of active solar water and space heating systems. In 1976, NRC began to assess the energy potential of solar heating systems by measuring the technology's state of development through a series of field trials. Fourteen active space-heating systems, both air- and liquid-based, were installed under contract to NRC. Located in new and existing single-family homes across Canada, the solar systems were designed to provide 30% or more of the space heating load and, in some cases, part of the domestic hot water heating load. Eleven sites had monitoring equipment installed to evaluate the performance of the solar systems.

By 1978, this project began to indicate that many problems could be encountered in constructing an operational solar heating system in a house, especially when the design, component supply, and installation were separate responsibilities. Nor did the solar systems generally meet their thermal goals.

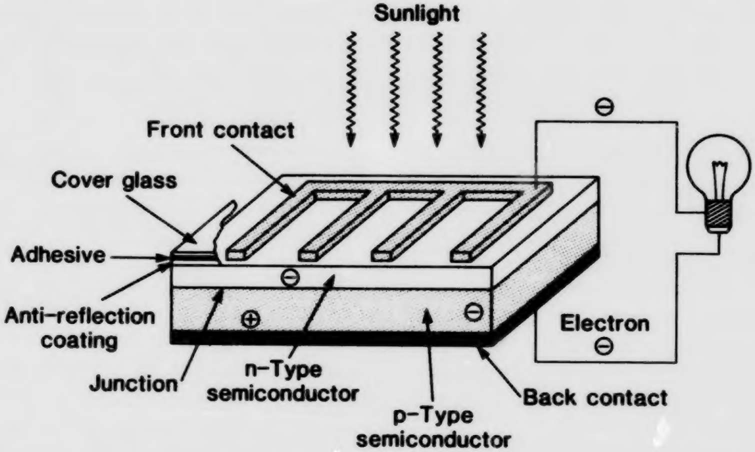


Figure 6 Operation of a photovoltaic cell

A solar cell contains a semiconductor junction — in this illustration, an n–p junction. When light is absorbed by a semiconductor, electrons and holes are created, which can move through the semiconductor lattice. The junction provides a charge separation mechanism: electrons can lower their energy by moving to the n side of the junction, and holes by moving to the p side. When contact is made to the front and back surfaces of the cell, a current flows, which can be used to power electrical devices (indicated here schematically by a light bulb).

System reliability proved a problem, as did a lack of expertise in design and installation.

The data from this project and others led to a policy based on the perceived need for additional research funding and a large well-financed demonstration program. The goal of this policy was to produce a new generation of dependable systems, augment design and installation expertise, and offer the opportunity to prove the economic viability of solar energy.

National Research Council Role in Solar Energy

The Canadian government's intention to encourage the development of an indigenous solar energy manufacturing industry and related infrastructure drew heavily on NRC expertise. By 1977, NRC had already set up its Solar Energy Program to develop the technical base for achieving the economic exploitation of solar energy.

This program supported the setting of product reliability standards, production of specialized texts on solar installation procedures, widespread dissemination of technical information, and the establishment of a national facility for testing solar collectors. The National Research Council also contracted groups in industry, plus university and other research organizations, to develop promising solar energy technologies, including specialized computer software to aid in the design of solar energy systems.

The Major Solar Energy Programs

The government introduced its major solar energy programs in the early summer of 1978. The Purchase and Use of Solar Heating program (PUSH) was budgeted for $125 million over a five-year period. Administered by Public Works Canada, its goal was the installation of Canadian-made solar space and water heating systems in buildings owned by the federal government.

The Program of Assistance to Solar Equipment Manufacturers (PASEM) had a $4 million budget and involved a competitive evaluation of equipment design, manufacturing capability, and marketing and business plans. Ten companies were awarded shared-cost contracts to develop and commercially produce solar heating equipment.

Outcome of Solar Energy Programs

In many ways the Purchase and Use of Solar Heating program and the Program of Assistance to Solar Equipment Manufacturers were successful. They generated employment (but not as much as initially hoped for), created a trade surplus in active solar systems, and produced notable technical innovations. However, they did not create a significant market for solar equipment. While only a fraction of the money designated for the Purchase and Use of Solar Heating program was actually spent, $26.1 million, the program nevertheless did fund 402 projects. Many would argue that this should have been sufficient to demonstrate the economic value of active solar systems.

The buying public also largely ignored solar energy systems. This can probably be attributed to the emergence of competing alternatives to solar energy products, along with the successful implementation of conservation measures.

Following a major interdepartmental review in 1982, the government set forth a new plan for active solar energy systems in 1983. The main aim was to enable the Canadian solar industry to become self-supporting within five years through the production of cost-effective products. A budget of $79 million was initially ear-marked for this research, development, and demonstration program.

After NRC closed its Solar Energy Program in late 1984, however, the Department of Energy, Mines and Resources announced it would restructure the 1983 solar energy program. In its place, EMR created the Solar Energy Development Program (SEDP) in early 1985.

The Solar Energy Development Program funds R&D and the demonstration of active, passive, and photovoltaic systems. A major goal of the program is to reduce substantially the cost of solar systems and enable industry to market products that are price competitive with other energy alternatives.

International Status of Solar Energy Technology

Leading Countries and Performers

Even after more than a decade of development, solar energy systems have not made great inroads in any of the major industrialized nations, although the number of solar domestic hot water heating systems is increasing in such countries as Australia, Israel, Japan, and Mexico. In arid Israel, for example, solar hot water systems on the roofs of buildings are a common sight. The technology is not sophisticated, but it is appropriate for a country with Israel's solar resource and general absence of freezing temperatures.

The oil shock caused virtually all Western nations to fund solar energy R&D programs. The United States and France committed substantial resources towards developing the solar power tower concept, in which a system of heliostats (reflectors) focuses the sun's rays onto a large receiver/boiler. The absorbed energy vapourizes a fluid which then expands in a turbine to produce electricity. The French Themis Project, as it was known, eventually proved uneconomic because of reliability problems associated with the particular technological route selected. Power tower demonstration plants continue to be funded in the United States.

The Dutch-based Philips organization produced evacuated tube collectors, resembling fluorescent lighting tubes. Solar radiation passes through the glass tube and heats metal fins attached to an inner metal pipe containing the heat transfer fluid. An advantage of such evacuated collectors is that energy losses from the heat transfer pipe due to convection and conduction are lower than in other collection concepts.

The nations most committed to solar were Japan, the United States, and

Sweden. Japan is heavily dependent on imported oil and embarked on a broad long-term solar program. It financed the development of flat-plate and evacuated tube technology and made an increasingly strong commitment to photovoltaic systems, providing $44 million to photovoltaic R&D in 1984 alone. The government also made low-interest loans available to residences and industry in an effort to encourage the spread of solar hot water systems. More than 500 000 units, with a retail price of $850 each, are being installed annually in Japan.

Sweden, meanwhile, having few energy options and a population nervous about nuclear energy, was quick to adopt building codes that promoted active and passive solar developments, including energy-efficient windows. The nation's industrial expertise was also tapped to build several solar-assisted district heating plants.

The United States moved swiftly to advance every aspect of solar technology through a variety of measures. To promote solar energy products, homeowners were given a 40% federal tax credit, often supplemented by state tax credits, on the first $10 000 spent toward the purchase of a solar energy system. In large part due to tax credits, the annual market for active solar systems in the United States reached about $1 billion in 1984. To provide some comparison, American production of solar collectors exceeded 1.5×10^6 m^2 in 1984, vs. an estimated 9.5×10^4 m^2 for Canadian production (much of which was exported). However, the cancellation of the solar energy tax credits in late 1985 has greatly reduced the sale of solar energy products in the United States and driven many companies out of business.

Research Agreements and Collaboration

To keep abreast of worldwide developments in solar energy research, Canada participated in the International Energy Agency's Solar Heating and Cooling Program. This program was divided into nine technical segments (called Tasks), with Canada participating in five.

Much of the work done by these Tasks was characteristically fundamental in nature. One group developed methods for testing the performance and durability of flat-plate collectors. Another evaluated evacuated tube collectors in solar heating, cooling, and hot water systems. Still another Task collected essential data regarding passive solar techniques, with NRC contributing valuable data through its monitoring of experimental test huts which employed several different passive solar designs.

The Atmospheric Environment Service of Canada acted as the operating agent for a Task investigating Solar Radiation and Pyranometry Studies. This involved not only improving pyranometers — devices that measure solar radiation — but also validating solar radiation models. They provide essential information about the amount and quality of sunlight striking the surface of the Earth.

In some cases, international collaboration proved useful in guiding national solar energy programs. For example, it had been suggested by some in 1979 that large centralized solar heating plants with seasonal storage would be a viable energy option in Canada. By participating in the Task studying this concept, Canadians were able to derive hard data that revealed the high costs of such solar facilities.

The Status of Solar Energy Technology in Canada

Active Solar

While the domestic market for active solar systems has turned out to be less than expected thus far, manufacturers have used government R&D funding to develop innovative products. Indeed, several have made inroads in the competitive American market.

The thermal diode collector, produced by Norsun, a division of Nortec Solar Industries Inc., Manotick, Ontario, is a unique Canadian design. Also known as a boiling/condensing collector with integral condenser, its operation has been compared to that of a coffee percolator. The collector consists of hollow "riser" tubes equipped with fins for absorbing solar heat. The solution of water and glycol in the riser tubes of the collector is heated by the sun until it starts to boil. The vapour bubbles travel up the riser tube and entrain liquid which, on reaching the top of the collector, spews out and splashes a "header" pipe carrying cooler water from a storage tank. The vapour condenses on this pipe and returns as a liquid to the bottom of the collector.

Because the diode collector has two separate fluid systems, one for absorbing heat captured by the collector and the other for carrying the water to be heated, freeze protection is made easier. Moreover, the freeze resistant water/glycol solution in the collector does not have to be circulated by a pump. Solar heat performs the task. As well, the system lends itself to a simplicity of design. A number of the collectors can be connected and a straight pipe carrying the cold water can be run through the top of them.

Petro-Sun Inc. of Montreal, Quebec, has gained notable success in supplying solar equipment manufacturers in Canada and abroad with a product called the Sunstrip. Production is highly automated and involves placing small-diameter copper tubing between two sheets of aluminum and fusing the aluminum sheets with high pressure. The copper tubing is only partially compressed. Solar collector manufacturers buy rolls of Sunstrip and are provided with special air pressure equipment that expands the tubing back to its original size and shape.

Petro-Sun and Solarsystems Industries Ltd. of Richmond, British Columbia, have developed advanced techniques for depositing thin films on solar absorber plates made of aluminum and copper. The thin films create a surface that is efficient in absorbing solar radiation but does not re-emit much infrared radiation. This improves the performance of solar collectors.

Government and industry R&D groups continue to pursue other advances in active solar technologies. A number of companies are now developing low-flow-rate active solar systems, which have significant potential for cost reduction. The concept is to reduce the flow of water from the storage tank by heating it to the desired temperature on a single pass through the collector.

The heated water is then returned to storage. Since the flow of water to and from the collector occurs at a low rate, the water in the storage system is not agitated. This allows stratification of water by temperature, that is, hot water remains at the top, while cold water rests at the bottom. Only the cold water is circulated to the collector for heating, thus improving thermal efficiency.

A key advantage of the low-flow-rate approach is that it permits the use of small-diameter piping between the collector and storage tank. Not only is this piping less expensive, but it also requires less labour to install. The end result is a cheaper system.

An improved low-flow seasonal domestic hot water system (DHWS), designed to operate in all but the four coldest months of the year in Canada, would contribute only 15% less energy annually than a domestic hot water system operating all year. Its estimated installed cost would be less than $1400.

L'Institut national de la recherche scientifique – Énergie (INRS) is helping some firms to develop refrigerant-charged collector systems which use fluorocarbons to transfer heat. Solar radiation heats the fluorocarbon liquid in the collector until it vapourizes. In the domestic hot water system, the vapour undergoes a phase change in the condenser, releasing heat to the storage tank. Refrigerant-charged systems offer fail-proof freeze protection and may not require electric pumps since the fluorocarbon can circulate under solar-induced vapour pressure.

Passive Solar

Another development that could produce significant energy savings in Canadian residences and offices is the super window, noted for its relative ability to prevent heat from escaping from the heated living space to the cold exterior. Super windows may have an RSI value of 1.0 or greater, several times better than the best windows generally available on the market today. (A reasonably well-insulated wall may have an RSI value of 3 to 4.)

Nonetheless, the performance of super windows is such that they can minimize the need for perimeter heaters in office buildings. Several factors account for the superior thermal performance of the super windows. They incorporate frames that impede heat conduction, glass panes may be separated by an insulating gas such as argon, and low-emissivity (low-E) coatings are applied on the appropriate glass surface.

The low-E coatings permit solar energy to pass through the window, but prevent all but a small amount of radiant energy in a house or office from escaping through to the outside. Although super windows are now appearing on the market, technical improvements are still being sought to bring down production costs. Researchers at Simon Fraser University, Burnaby, British Columbia, for example, are developing a promising technique for spraying uniform layers of low-E coatings on glass.

Corona Vacuum Coaters Ltd., Vancouver, British Columbia, has developed an innovative magnetron sputtering unit that deposits layers of oxides and metals — only atoms thick — on plastic film. Stretched on a frame, this film can serve as the intermediate pane for sealed triple- or quadruple-glazed windows.

The development of the Light Pipe by TIR Systems Ltd. of Burnaby, British Columbia, could exert a profound influence on building design and promote the spread of passive solar lighting techniques (see Figures 7 and 8). The original Light Pipe resembles plastic ducting, except that the outside surfaces have angular ridges. These are actually prisms that reflect the light being guided through the duct. More recently, TIR has greatly reduced the physical size of the prism ridges and, consequently, has been able to integrate them into thin films.

With the advent of such technology, it is possible to contemplate the design of commercial buildings containing only a fraction of electrical lighting fixtures found in existing buildings. Natural light, or light from high-efficiency lamps, could be piped into the work areas. The light may originate from outside the main building envelope.

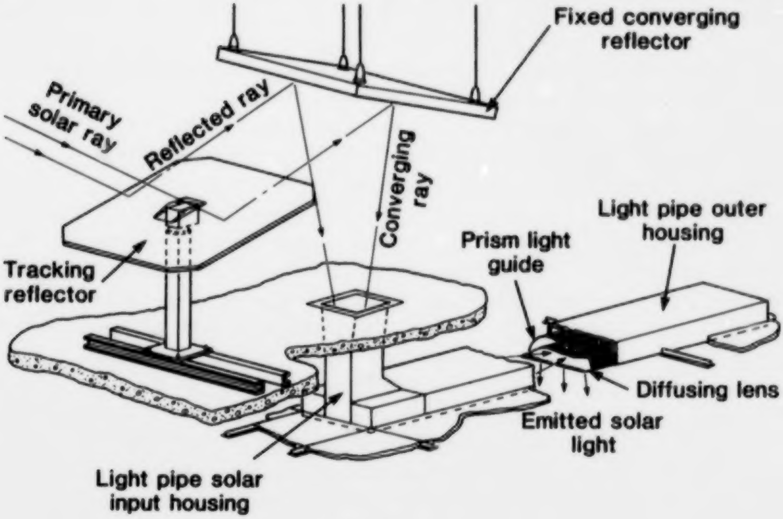

Fixed converging reflector
Primary solar ray
Reflected ray
Converging ray
Light pipe outer housing
Prism light guide
Tracking reflector
Diffusing lens
Emitted solar light
Light pipe solar input housing

Figure 7 Light Pipe installation

A typical solar Light Pipe installation, showing schematically how sunlight is reflected by computer-controlled heliostats to mirrors on the ceiling, which re-direct the sunlight down to 8-in.-wide ducts housing the Light Pipe.

Such a system could drastically reduce electrical energy consumption for cooling buildings and lessen the load on air-conditioning systems which, in some Canadian office buildings, operate even during winter months. (High-efficiency lamps convert about 10% of electrical energy into light; the rest is converted into heat. The incandescent lamp performs more poorly, converting 1.6% of electrical energy into light.)

Developments such as the super window and light-conducting ducts represent only two of many R&D thrusts in the passive solar field. The National Research Council's monitoring of several passive solar houses, to cite another case, yielded important data on making the best use of solar energy that enters buildings through windows, atria, and sunspaces.

In addition, efficient and inexpensive ways of transferring heat from one part of a building to another are under investigation, as are curtain walls that can selectively reflect or absorb solar radiation and phase-change materials for storing solar heat in walls.

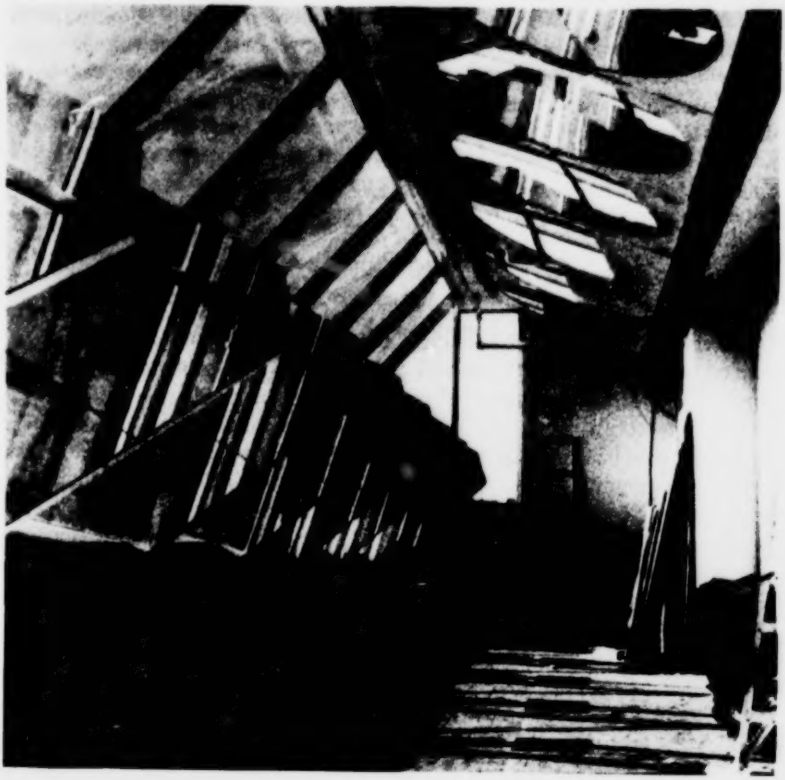


Figure 8 The heliostats and ceiling mirrors of a Light Pipe installation

Photovoltaics

Although Canada is not a major player in the production of solar cells, manufacturers are successfully exploiting market niches. TPK Solar Systems Inc., Nepean, Ontario, has sold its module production systems (which contain the interconnected solar cells) to China and India. The company has also developed a photovoltaic water pumping system for less-developed countries.

Another noteworthy Canadian achievement was the development of a special reverse osmosis desalination process that is powered by photovoltaic devices. The energy recovery pumps of the system are highly efficient, maintaining a high ratio of output power to input power over a wide voltage range. Other systems may operate efficiently at a fixed voltage and current, but if these conditions vary, the ratio of energy output to energy input greatly decreases.

Computer Simulation and Solar Energy

The computer has been a valuable and much-needed tool in the drive to tap the energy of the sun. Without computerized aids, this effort would have been slowed considerably.

The Atmospheric Environment Service of Environment Canada produced a powerful solar simulation model known as *MAC.3*, one of the most advanced in the world. *MAC.3*, which contains data applicable in 129 locations across Canada, was developed to estimate hourly solar radiation and its direct and diffuse components. Techniques have been developed to convert the information on direct and diffuse radiation, plus that from ground reflections, into radiation values for inclined surfaces. The observed or estimated data have been put into formats that are usable for a wide variety of purposes. For example, the hourly data of solar radiation, temperature, and wind speed, over a 10-year period, are available on computer tape for a large number of Canadian cities.

Watsun, developed at the University of Waterloo, Waterloo, Ontario, simulates the performance of active solar systems. This is done by mathematically representing the physical description of the system, its components, and the meteorological data. These mathematical representations are then combined with the equations of conservation and solved at each hour to simulate the performance of the system. Originally developed for a large computer system, the software is now available on a disk for use in a microcomputer.

Hotcan is a model developed at NRC to aid in the design of energy-efficient buildings. By providing the program with data about the physical structure and location of a house, *Hotcan* estimates passive solar gain, as well as computing overall energy consumption.

Vision simulates the thermal performance of window designs, using equations to calculate heat loss, the optical properties of glazing, and the effect of pane spacing in reducing energy loss by conduction through air.

Other Achievements

Canadian solar collectors, noted for their reliability and durability, are tested at the National Solar Test Facility (NSTF) in Toronto. This NRC facility is operated by the Ontario Research Foundation (ORF) and has earned a worldwide reputation for the quality of its testing.

To be accepted for the Canadian marketplace, solar collectors must undergo a series of tests at the National Solar Test Facility, including 30 days of exposure to the outside elements to test for corrosion (see Figure 9). This facility is also equipped with the world's most powerful lamp, a 125 000-W plasma arc lamp developed by Vancouver-based Vortek Industries Ltd. The light from this plasma arc lamp shines on a solar collector through which water is circulated at appropriate test conditions. Since the amount of radiant energy on the collector is controlled, the efficiency of the collector can be determined by measuring and comparing the temperature of the incoming water to that of outgoing water. Solar collectors, solar domestic hot water

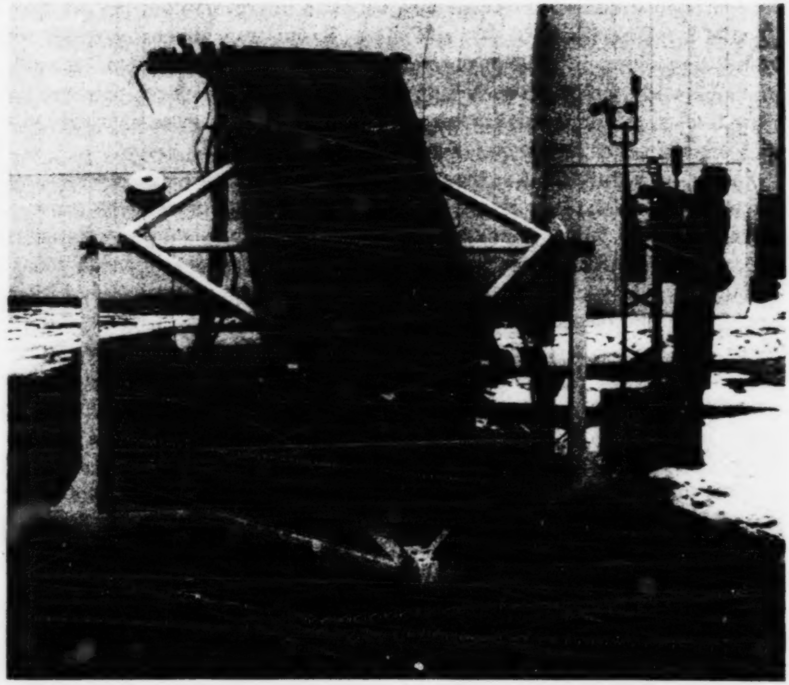


Figure 9 Solar collector undergoing tests at the National Solar Test Facility in Toronto

systems, photovoltaic modules, and photovoltaic water pumping systems are tested at the National Solar Test Facility, according to the test procedures of the Canadian Standards Association and other organizations.

Some of the Canadian-developed systems that the National Solar Test Facility employs in its testing of solar energy products have been sold to Italy, and other international sales appear plausible.

Economic Prospects for Solar Energy Products

Despite certain disappointments, solar energy systems will, in the longer term, contribute to Canadian energy self-reliance. Indeed, the exploitation of passive solar energy techniques is decidedly economic today in many applications.

It is estimated that orienting windows towards the south, reducing heat loss through windows, and other measures can improve the energy performance of a typical house by 20 to 25 GJ/a. Based on new housing starts and retrofitting activities, some have estimated that passive solar techniques could contribute 100 to 200 PJ in cumulative energy savings between now and the year 2000 in the residential sector alone. Significant energy savings may also be realized in commercial buildings.

While it is difficult to estimate the market for passive solar energy products, it promises to be large. The domestic market for windows alone is worth about $1 billion annually. Should super windows gain acceptance in the marketplace, their sales could easily reach hundreds of millions of dollars per year.

Meanwhile, the economic future for active solar systems is less certain. With cost reduction breakthroughs, it is possible that a viable commercial market for active solar water heating could emerge in Canada during the next decade. Clearly, the original expectations for active solar products have been thwarted by the realities of system cost and the low price of conventional energy.

The active solar manufacturing industry is small, consisting of about a dozen companies with hardware sales totalling $15 million in 1985. Canadian companies are designing innovative products and export 50% of their production, mainly to the southern United States. As mentioned earlier, the removal of tax credits for solar products bought by American consumers is starting to hurt manufacturers of solar energy products in that country.

Moreover, prospects for active solar systems in Canada are not encouraging for the short term. According to EMR estimates, the energy currently produced by active solar systems amounts to about 400 000 GJ/a (0.4 PJ/a); relative to the supply/demand data of Chapter 1, this contribution is clearly modest.

The cold climate is part of the reason. Domestic hot water systems must be protected against freezing and this can increase the cost of a system by 50% over one not requiring freeze protection.

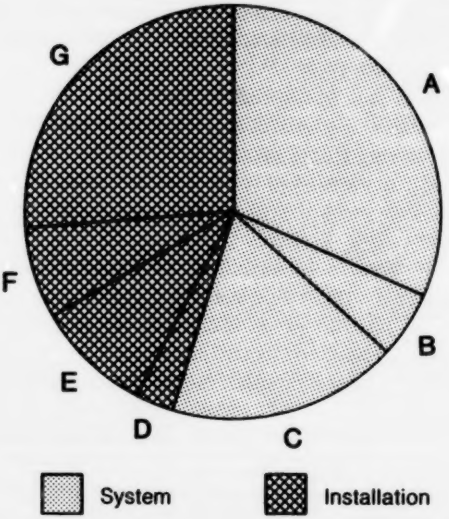
At present, a solar domestic hot water system having an energy output of 8 to 9 GJ/a, sufficient to meet 50% of the hot water requirements of a typical Canadian home, costs about $2500 to $3000 installed. In addition, a back-up water heater would have to be installed, an expense of several hundred dollars. Assuming that electric water heating is used as the backup source (at 5¢/kWh, or $14/GJ), annual cost of electricity for water heating would be $112 to $126. By comparison, an electric hot water heating system capable of meeting all the needs of most Canadian homes would involve annual heating costs of $220 to $250.

The National Research Council has determined that, based on current prices for conventional energy, solar water heaters could compete in the market if installed capital costs were reduced to 40% of the current cost. It is clear that achieving this goal represents an immense challenge, since significant cost improvements must be made on several fronts. In a $3000 solar domestic hot water system, this includes the collector (32% of the cost), labor (26%), and tank and heat exchanger (18%). Figure 10 presents a cost breakdown of a domestic solar hot water heating system.

Another important factor has impeded the wide-scale application of solar water heaters. They have not drawn the interest of electrical utilities because even widespread implementation of current designs would not significantly reduce the peak load demands placed on Canadian electrical systems. The heaviest demand for electricity occurs during the winter months, when the contribution of solar water heaters would be at its lowest point.

Active solar heating systems have not penetrated the low-temperature commercial and industrial process heating (CIPH) market to any extent. This is the case even though some solar commercial and industrial process heating systems cost $130 to $195 per gigajoule per year. The current target is to bring this down to $50 per gigajoule per year. Figure 11 presents a cost breakdown of a commercial and industrial process heating system.

Many of the applications originally envisaged for solar commercial and industrial heating systems proved to be more economically served by heat pumps and heat exchangers. In some hockey rinks and dairies across Canada, for instance, the heat recovered from large refrigeration systems is used to



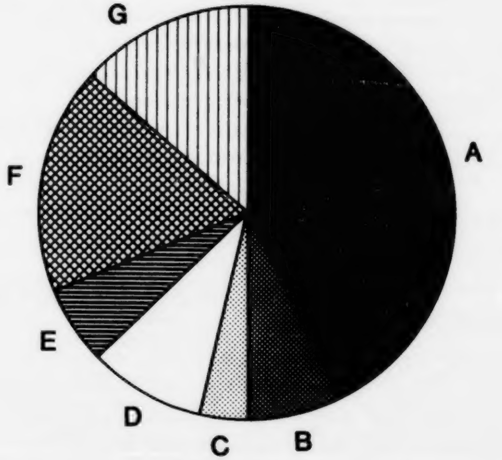
A Collector	32%
B Pump and controller	5%
C Tank and heat exchanger	18%
D Collector mount	3%
E Plumbing	9%
F Insulation	7%
G Labour	26%

Total Cost: $3080

Figure 10 Cost breakdown for a solar domestic hot water system

preheat incoming cold water. Still, solar-based commercial and industrial process heating systems are economic in certain applications, such as car washes, fish farms, and swimming pools.

Photovoltaic systems are not likely to contribute significantly to the energy supply for some time yet. Notwithstanding drastic decreases in production costs of solar cells during the past decade, electricity generated by



A	Collector price, transport, and mounting (no plumbing)	43%
B	Project feasibility and design	7%
C	General construction	4%
D	Storage, heat rejection provisions	9%
E	Controls, heat meter, and electrical connectors	6%
F	Plumbing, piping, heat exchanger, piping insulation	18%
G	Collector support structure	13%

Figure 11 Cost breakdown for a solar commercial and industrial process heating system

An active solar heating system for an industrial or commercial application would cost about $350/m^2 to install (if single-glazed metal collector technology was used). Relative costs of the main components of such a solar CIPH are listed here.

photovoltaic devices continues to be very expensive compared to grid power. A system that generates 280 W at its peak (when the intensity of solar radiation is at its highest point) costs more than $7000. It consists of an array of solar cells, batteries, a charge regulator, and an inverter for converting direct current into alternating current.

Photovoltaic systems can be virtually maintenance free, so in a narrow range of applications they are now economically justified by eliminating, for instance, frequent helicopter trips to remote regions to replace the discharged batteries of an isolated weather monitoring station.

To date, more than 2000 photovoltaic systems have been sold in Canada and the annual market is thought to be worth $3 million (excluding the tiny solar cells on watches, calculators, and other consumer electronics). Most of these systems operate in remote sites, providing electrical power to navigational aids, telecommunications gear, and monitoring instruments.

Recommendations

Regarding solar energy technology, it is recommended that:

1. Simpler, faster, and cheaper techniques should be developed for simulating the performance of solar energy systems on microcomputers, to speed the development of cost-effective solar energy products and to improve the effectiveness of passive solar applications.
2. Carefully planned well-instrumented field tests on prototype solar products should be continued to ensure rapid and accurate feedback on new systems and components. Well-documented field experience lends credibility to companies selling in the export market, especially with the rapid change in solar energy technologies.
3. The use of Canadian photovoltaic products should be encouraged for domestic applications by continuing work on test methods and standards, as well as by performing appropriate monitoring. National acceptance of Canadian-made products is necessary if Canadian firms are to penetrate international markets.
4. The focus on active solar systems should be aimed at cost reduction and improved reliability, with the emphasis placed on simple lightweight systems and components.
5. Industrial activity should be encouraged in the development of super windows, with the emphasis on integrating new concepts in glazing and framing to produce highly energy-efficient systems.

3 WIND ENERGY

Description of Wind Energy Technology

The first windmill was used 13 centuries ago in Persia to grind grain. While primitive compared to today's computer-designed machines, the working principle was the same: it converted the kinetic energy in a moving air stream into mechanical energy.

Throughout history, windmills have been employed to grind grain, saw lumber, and pump water. They were a common sight at one time; in the 1600s, for instance, an estimated 20 000 windmills were operating in the Netherlands alone.

More recently, in the early 1900s, small multiblade windmills were used on many North American farms to pump water or to charge batteries that powered a few lights and a radio. More than five million windmills were in use until rural electrification programs provided cheaper and more convenient power.

Today, two basic types of windmills, or more properly wind turbines, as they are now called, are undergoing intense development. The horizontal-axis wind turbine (HAWT) is the most common at present; the axis of rotation of its propellor-like rotor is parallel to the wind stream and to the ground. More recently, a certain type of vertical-axis wind turbine (VAWT), shaped like a giant two-bladed eggbeater, has been gaining greater acceptance in international circles — largely because of NRC's work. Sometimes called the Darrieus wind turbine, after its French inventor Georges Darrieus (his 1927 invention had been forgotten until re-invented by NRC in the mid-1960s), the axis of rotation of this wind machine is vertical, that is, perpendicular to the wind stream and to the ground.

Whether it has a vertical axis or a horizontal axis, a wind energy conversion system (WECS) comprises five basic subsystems (see Figure 12): the rotor, which converts the kinetic energy of the wind into mechanical energy on a shaft; a drivetrain, which may include a gearbox, brakes, generator, or pump; a tower for supporting the rotor; a control and protection system; and balance-of-station subsystems including interconnection equipment.

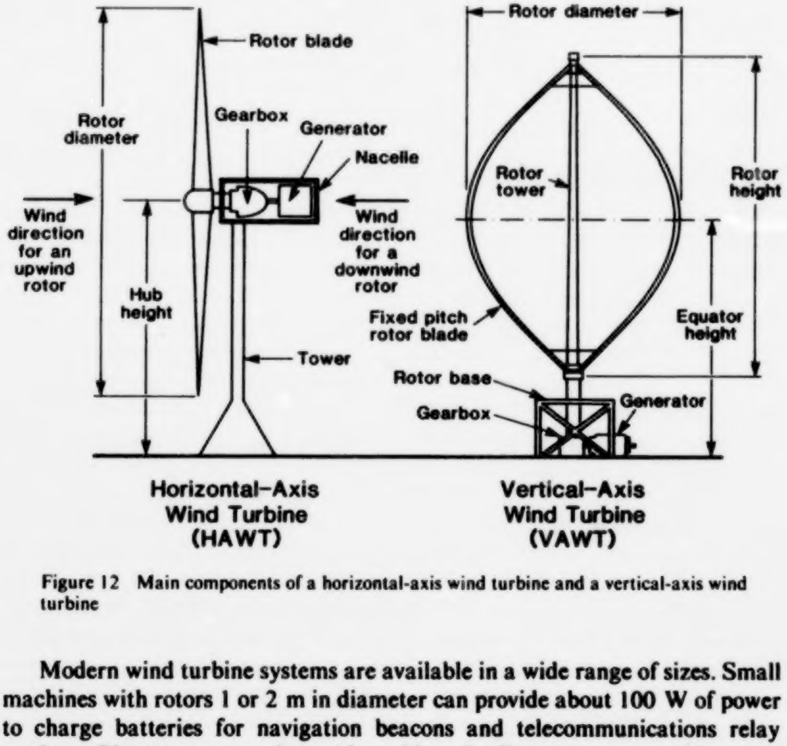

Rotor blade
Rotor diameter
Gearbox
Generator
Nacelle
Wind direction for an upwind rotor
Wind direction for a downwind rotor
Hub height
Tower
Horizontal-Axis Wind Turbine (HAWT)
Rotor diameter
Rotor tower
Rotor height
Fixed pitch rotor blade
Equator height
Rotor base
Gearbox
Generator
Vertical-Axis Wind Turbine (VAWT)

Figure 12 Main components of a horizontal-axis wind turbine and a vertical-axis wind turbine

Modern wind turbine systems are available in a wide range of sizes. Small machines with rotors 1 or 2 m in diameter can provide about 100 W of power to charge batteries for navigation beacons and telecommunications relay stations. Bigger systems about 10 to 20 m in diameter can provide up to 100 kW for remote communities or, in multi-unit clusters, to regional electric networks. The largest systems, with rotors up to 100 m in diameter and capable of generating several megawatts, are in the early stages of development for electric utility applications.

Several factors play a role in determining the performance of wind turbines. Foremost among these is annual average wind speed — the wind regime — at the selected site. The power that can be extracted from the wind increases with the cube of the wind speed; in theory, a wind turbine extracting 1 kW of power from a wind moving 5 m/s will extract 8 kW of power from a 10 m/s wind.

Winds are variable and hence the wind turbine output power varies greatly with time. It seldom operates at full power and during calm periods, of course, does not operate at all. Thus the energy produced by the wind turbine is strongly dependent on the average wind velocity at the site.

Additionally, wind speed increases with height and it is therefore advantageous to place turbines on tall towers and tops of hills. For every doubling of the height above flat terrain, the wind speed increases 12%; this ratio increases in rough terrain.

A detailed analysis of the wind regime is also important in matching the rotor and a generator to obtain the proper power loading (generator rated power in watts per square metre of rotor swept area). Generally, a machine that has a very high power loading (1000 W/m^2) is best suited for very strong wind regimes. In a modest wind regime, the rotor should be large relative to the size of the generator. In a wind regime under 5 m/s, the power loading should be low, less than 250 W/m^2. Although a similar-sized rotor could be attached to a generator that is twice as large and have a power loading of 500 W/m^2, it would actually produce 25% less energy at an average wind speed of 5 m/s.

A well-designed unshrouded wind turbine, one having no wind funneling structures, can realistically be expected to extract a maximum of 40–42% of the kinetic energy from moving air, although 59.3% is the theoretical maximum. Average conversion efficiencies, accounting for operation at other than design wind speed, are typically 30–35%, including drivetrain and generator losses.

Program Rationale and Background

The National Research Council has been doing wind energy research since 1966, when two engineers at the Low Speed Aerodynamics Laboratory began investigating wind turbines as a means of producing small quantities of mechanical or electrical energy in less-developed nations. It was their work that less than a decade later would prompt the wind energy program to pursue further development of the Darrieus wind turbine.

National Research Council Role in Wind Energy

When international interest in wind energy escalated in the 1970s, NRC refocused its wind energy program to determine whether such systems could produce economical energy on regional and national scales in Canada. The revised program also sought to establish wind turbine technology appropriate to Canadian climatic conditions, encourage development of an indigenous industry to design and manufacture wind turbines, and provide objective technical information to developers, manufacturers, dealers, and other users of wind energy technology.

From the National Research Council's perspective, the vertical-axis machine had numerous advantages. Being omni-directional, it does not require, as does a horizontal-axis machine, a yawing mechanism to keep properly oriented to the wind. Moreover, the drivetrain is located below the rotor shaft and not on an expensive tower where access for maintenance is more difficult. Also, the rotor blades can be designed to stall aerodynamically in high winds, thereby regulating power production automatically. (When the wind exceeds a certain speed, the blades begin generating a smaller lifting force; the principle is the same as an airplane flying at too steep an angle and "stalling" aerodynamically.)

The National Research Council's analyses of the horizontal-axis and vertical-axis wind turbines revealed that the latter machine had a peak power efficiency at least equal to the horizontal-axis machine. Based on these findings and wind tunnel tests of many small models, NRC decided to develop further the Darrieus wind turbine.

Construction of early field-trial prototypes was contracted to Canadian industry. The first utility-scale machine had a power rating of 224 kW and was produced by DAF Indal Ltd. (now known as Indal Technologies Inc.). In subsequent years, several firms developed prototype systems and various subsystems under contract to NRC. This, plus collaborative field test projects using 50-kW units, was to ensure effective transfer of the evolving wind energy technology to both manufacturers and potential users.

The National Research Council's wind energy program supported a variety of related research activities. The Atmospheric Environment Service of Environment Canada conducted detailed analyses of the nature and extent of Canada's wind resource. This involved developing analytical and experimental modelling techniques, testing a variety of wind measuring instruments, and evaluating sites for their wind energy potential.

For the designers of wind turbines themselves, modelling techniques were developed to assess how a system would perform in a given wind regime and what the optimal configuration would be.

Analytical and experimental research projects improved rotor aerodynamic qualities, while structural dynamic analysis and design methods were also developed. Such research is important because a rotor can be subjected to several modes of vibration, each having a resonant frequency that can amplify stress and eventually cause fatigue failures.

For water pumping applications, tests were performed on a horizontal-axis wind turbine invented at the University of Calgary and manufactured by Alberta-based DELTX Windpumps Ltd. The company believes a substantial market exists for large- and farm-scale wind-driven water irrigation pumps.

Another important mandate of the wind energy program involved testing the performance and reliability of commercial prototypes and, to this end, the Atlantic Wind Test Site was set up by the federal and provincial governments at North Cape, Prince Edward Island. As well, Alberta Agriculture established the Windpump Test Site at Lethbridge.

International Status of Wind Energy Technology

Leading Countries and Performers

The exploitation of wind energy in the United States has been the most dramatic of any nation's. To date, considerably more than 1400 MW of wind turbine capacity has been installed, mostly in California. By the fall of 1985, more than 17 000 wind turbines — valued at $2.6 billion — were operating in that state and had produced the electric energy equivalent to one million barrels of oil, about 600 GWh. Most of the Californian wind farms have been erected in the Altamont, San Gorgonio, and Tehachapi Passes in California, where the annual average wind speeds exceed 7 m/s.

Federal and state energy tax incentives have helped to stimulate the sale of wind turbines (and other renewable energy technologies) in the marketplace. Equally important, the Public Utility Regulatory Policies Act of 1978 required utilities to buy power from owners of renewable energy projects at rates based on the utility's avoided (marginal) cost of power.

On the technical side, the American wind energy program sponsored the development and installation of several multimegawatt wind turbines. Among the largest of these are three 2.5-MW machines which began operating in 1982 at Goodnoe Hills, Washington. These large wind turbines have experienced some problems, including structural cracks and control system malfunctions, that have caused nuisance shutdowns. However, all are still operating.

The leading European developers and appliers of wind turbines have all accumulated considerable experience with small systems. They have since embarked on programs to develop and install intermediate- and megawatt-sized machines.

In Denmark, the European country most advanced in designing and developing small horizontal-axis systems, several wind farms are being constructed and will use small- and medium-sized wind turbines. As well, a regional power company is building a 2-MW horizontal-axis that is expected to be operating by mid-1987.

Sweden's wind energy program, begun in 1975, has concentrated on the design and construction of 2- and 3-MW wind turbines. The 3-MW machine at Maglarp, a two-bladed horizontal-axis system, was connected to the grid in 1982 and has since produced more than 12 000 MWh of electrical energy. The government is undertaking a siting study for wind farms in the expectation that such farms could ultimately generate 10×10^6 MWh/a on land and 20×10^6 MWh/a offshore.

Energy officials in West Germany conservatively estimate that 345 large wind turbines and 7800 smaller ones could generate more than 1.3% of the country's electricity by the year 2000. The government has helped to fund a long-term program to develop a 5-MW single-bladed horizontal-axis wind turbine; a 370-kW prototype is now functioning. Utilities, manufacturers, and various levels of government are discussing plans to build two demonstration 1-MW wind farms.

In the Netherlands, wind energy is seen as the most important of the available renewable energy sources. The government believes 1000 MW of wind power can be installed by the end of the century. Large-scale wind turbines will account for most of this installed base.

The United Kingdom's wind energy program currently emphasizes land-based machines, although the major potential for wind energy lies in offshore installations in the shallow waters surrounding England. Studies based on wind regime measurements and projected cost/performance of large offshore wind energy systems suggest that as much as 10% of the United Kingdom's electrical energy could eventually be supplied by wind energy technology. A variety of horizontal- and vertical-axis wind turbines are under development in the United Kingdom, including a 3-MW horizontal-axis machine and a 300-kW prototype of a novel arrowhead vertical-axis system.

Research Agreements and Collaboration

Canada has participated in both of the International Energy Agency's wind energy agreements; it joined the first, involving wind turbine research and development, in 1977. Over an eight-year period, Canada participated in five of nine major collaborative research projects. Three of these concerned environmental and meteorological aspects of wind energy: the study of local wind flow at potential wind turbine hill sites (headed by Canada), the investigation of wake effects produced by wind turbines, and the operation of wind/diesel hybrid systems.

In 1982, after the federal government approved the 4-MW Project ÉOLE, Canada also signed IEA's Large-scale Wind Energy Conversion Systems agreement. The seven national participants of this agreement exchange detailed technical information regarding the development and operation of megawatt-scale systems and also hold specialized technical meetings. Topics discussed cover a wide range of subjects, such as fatigue problems associated with rotor blades, the modelling of atmospheric turbulence, reliability and maintenance problems, economic aspects of wind turbines, and structural design criteria. Canada chaired the executive Committee of IEA's large-scale wind turbine agreement from 1983 to 1985.

The Status of Wind Energy Technology in Canada

Since the beginning of the federal government's interdepartmental energy program in 1974, Canadian wind energy R&D projects have been predominantly contracted out to Canadian industry. The technical foundation from earlier research at NRC has been used to establish analytical and experimental techniques. A primary goal has been the development of the aerodynamic, structural, and systems engineering design tools needed to create more cost-effective machines.

The First Utility-scale Vertical-axis Wind Turbine

A 224-kW vertical-axis wind turbine, designed by NRC and built by DAF Indal, marked an important milestone in the international wind energy community. Erected on the Îles de la Madeleine in 1977 by NRC and Hydro-Québec, it was not only huge by the standards of the time but proved the basic concepts of utility-scale vertical-axis turbines. Although a procedural oversight during maintenance resulted in severe overspeed and subsequent collapse of the rotor, it was rebuilt a year later and continued to provide data until the end of the NRC program.

The 50-kW Family of Vertical-axis Wind Turbines

DAF Indal's collaboration with NRC on the 224-kW wind turbine helped provide the company with technical expertise for designing its own 50-kW vertical-axis wind turbine. The National Research Council bought four of the thirteen 50-kW units, which DAF built, for cooperative field test projects throughout Canada. Others were sold to the United States, Australia, and Ireland. Many design innovations were incorporated on this series of machines, and all Canadian units remain operational. Most have run more than 15 000 h (see Figure 13). These 50-kW machines were built strictly as prototypes for utilities and others to test and, although expensive, they did earn an international reputation for high performance and reliability.

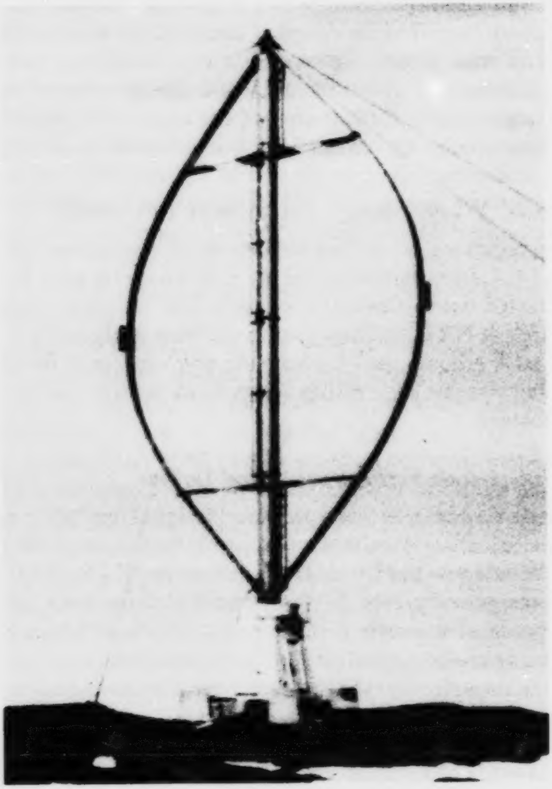


Figure 13 50-kW wind turbine manufactured by Indal Technologies, operating at Churchill, Manitoba

Project AQUILO

Based on experience gained from the 224- and 50-kW machines, Indal designed and built its 500-kW commercial unit, currently the largest operating vertical-axis wind turbine in the world. The first such machine was bought by Southern California Edison Co. for its testing center near Palm Springs. The National Research Council bought the second one (nicknamed AQUILO) at a cost of about $600 000 and installed it at the Atlantic Wind Test Site in Prince Edward Island in November 1983 for a period of extensive testing (see Figure 14).

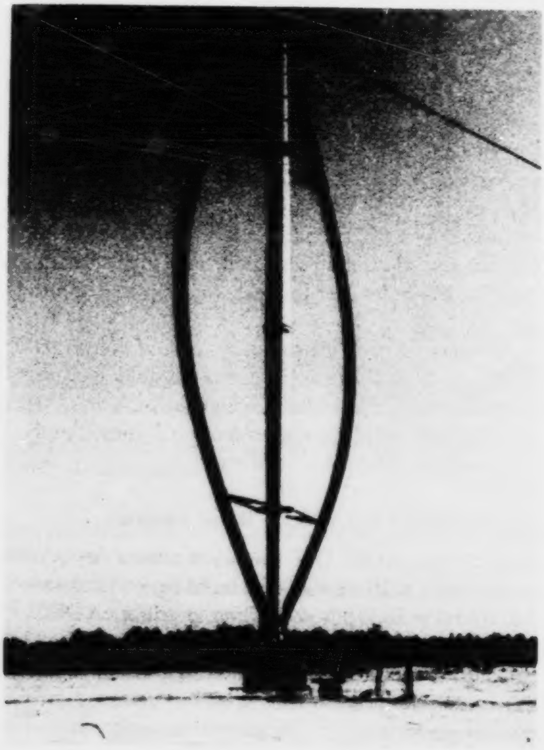


Figure 14 The 500-kW AQUILO wind turbine manufactured by Indal Technologies, Atlantic Wind Test Site, Prince Edward Island

AQUILO is designed for high-wind regimes, as indicated by high power loading of nearly 900 W/m². The rotor is 37 m high and has an equatorial diameter of 25 m. The blades are made of extruded aluminum. AQUILO embodied a number of design innovations by Indal, including a simpler one-step (rather than multi-step) gearbox, a hydraulic support arrangement that controls guy wire tension, and fail-safe gravity applied brakes.

The AQUILO testing program demonstrates the sophistication of contemporary wind turbine evaluation. For instance, 40 strain gauges were placed on the blades and central rotor column. Tension load cells were attached to each of the guy wires, while motor/generator shaft speed and electrical power output were also monitored, as often as 20 times per second. Sensors recorded ambient air temperature and barometric pressure, while anemometers and direction sensors measured wind conditions. The data generated by the various electronic devices were relayed to computers at the Atlantic Wind Test Site and NRC laboratories, providing a detailed and accurate report of AQUILO's performance.

After two years of operation, AQUILO met a temporary set-back in late 1985 when one of its rotor blades broke. An investigation concluded the breakage was caused by a fatigue failure of the blade material adjacent to the bolt holes that connect the blade to the strut. Tiny stress cracks had developed around one of the holes and the salt water spray from the nearby ocean promoted corrosion.

The whole purpose of such testing programs, of course, is to detect flaws. A positive aspect of AQUILO's failure was that the control system worked perfectly, conducting an orderly shutdown of the machine. Although an extra blade was available and could have been mounted immediately, Indal decided to re-design the strut to avoid future failures.

A Different Approach to Vertical-axis Wind Turbines

In the early 1980s, ADECON Energy Systems Inc., Weston, Ontario, took another approach to designing and building vertical-axis wind turbines. In contrast to Indal's high-power-loading product, ADECON decided to design a medium-power, low-cost machine. The rotor is 25.5 m high and 17 m wide, giving a swept area of 283 m² and a power loading of 442 W/m² for its 125 kW rated power.

Its appearance is strikingly different from most vertical-axis machines (see Figure 15). The 125-kW machine is supported by an external lattice framework, not guy wires. ADECON has thus eliminated the compressive force the guy wires exert on the rotor column, bearings, and gearbox. Also,

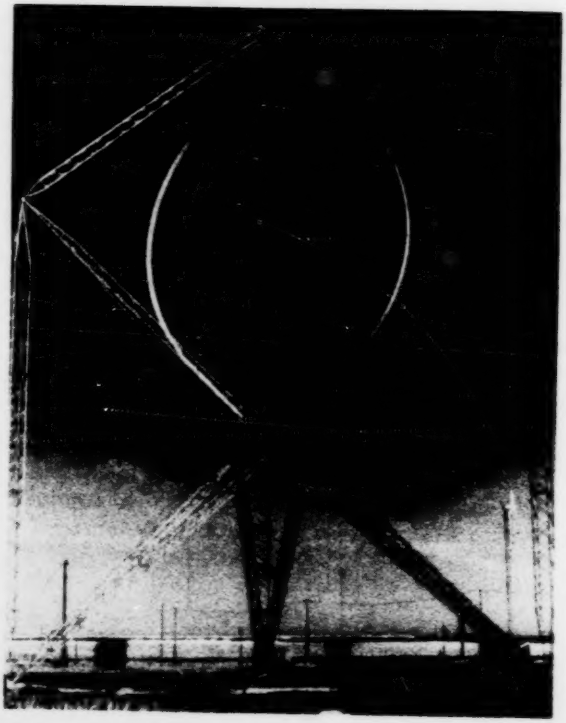


Figure 15 The 125-kW wind turbine built by ADECON Energy Systems, Atlantic Wind Test Site, Prince Edward Island

the framework positions the rotor about 15 m above the ground to take advantage of increased wind speed.

The rotor blades, too, are radically different from those on other vertical-axis machines. They do not consist of single aluminum extrusions (which can be provided only by a few companies in the United States), but comprise four smaller aluminum extrusions glued together using bonding technology developed for the aircraft industry. The lighter blades and the elimination of guy wire pressure permit the use of standard bearings, gearbox, and other drivetrain components (which are cheaper than customized components).

ADECON maintains it can provide the machine for an installed cost of under $1000/kW, well below the factory cost of most other wind turbines.

The ADECON prototype has undergone preliminary testing at the Atlantic Wind Test Site and the company is building its own 19-m diameter test machine near its factory in southern Ontario. This wind turbine will feature further innovative technical and cost reduction features.

Project ÉOLE

Studies in Canada and other countries have shown that the cost effectiveness of grid-coupled wind turbines improves with increasing size, up to a rating of several megawatts. To investigate the design, fabrication, erection, and operational characteristics of very large vertical-axis wind turbines, Hydro-Québec and NRC jointly financed the construction of the world's largest vertical-axis machine at La Fonderie, a small community near Cap Chat in Quebec's Gaspé region. The 4-MW machine has a height of 96 m (making it taller than the Peace Tower of the Parliament Buildings), an equatorial diameter of 64 m, and a swept area of 4000 m^2 (see Figure 16). The steel blades have a chord (width) of 2.4 m and the rotor column is 5 m in diameter.

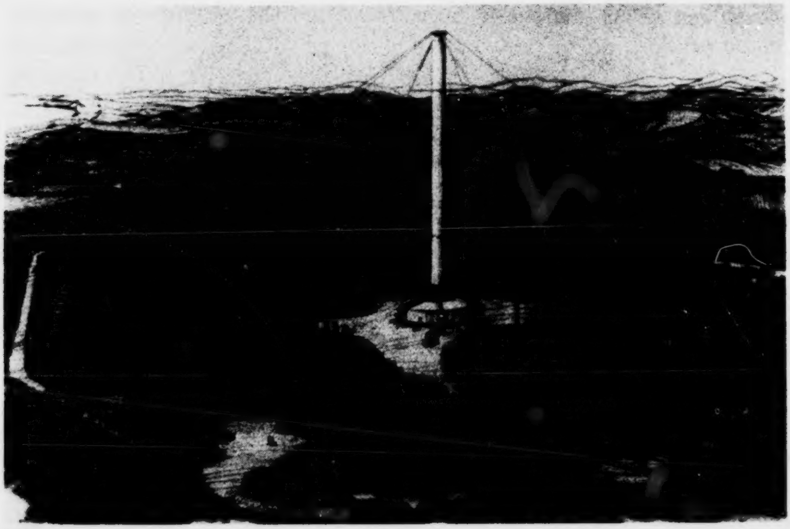


Figure 16 The 4-MW ÉOLE wind turbine, to be erected in 1986 near Cap Chat, Quebec

The machine is unique not only in its size but also for its simplicity. For example, it avoids the need for an expensive gearbox. Instead, the rotor shaft turns a large flat 13-m diameter generator at rotor speed, about 14 rpm. A static frequency converter (SFC) converts the low-frequency AC power produced at the generator into DC, then inverts it to 60-cycle, grid compatible electricity. Connection to the grid will be made to nearby 69- and 265-kV transmission lines through step-up transformers.

The average annual wind speed at ÉOLE's site is 9 m/s. The wind turbine will cut in when wind speed exceeds 5.5 m/s and it will cut out when the wind speed reaches 20 m/s. However, it is designed to survive a wind speed of 65 m/s.

The total cost to design, build, install, and evaluate ÉOLE, as well as to prepare the site, will be $35.2 million. Construction of the wind turbine components is nearly complete and the first electricity is expected to be generated before the end of 1986.

Hydro-Québec is ÉOLE's project manager, with Experts-Conseils Shawinigan Inc. (ECSI) of Lavalin as the engineering contractor. The rotor is being manufactured by Versatile Vickers Inc.; Canadian General Electric provided the generator, static frequency converter, and controls; and Hayes Dana Corp. supplied the drivetrain.

ÉOLE continues to be the focus of attention of the international wind energy community, as it has been almost since its inception. When ÉOLE's design was first completed, wind energy experts from several countries came to Montreal for a week to offer their comments and suggestions.

From a scientific point of view, ÉOLE will also prove whether the analytical design tools have been accurate in determining such factors as vibrational characteristics and stress levels. These are of particular interest to Sandia Laboratories of Albuquerque, New Mexico. As the focal point of Darrieus wind turbine research in the United States, Sandia has played a key role in developing these analytical tools.

In keeping with the aim of technology transfer to industry, Hydro-Québec and NRC decided in May 1986 to transfer ownership of ÉOLE to ECSI/Lavalin. The new owners have assumed responsibility for completing the fabrication, plus the assembly, commissioning and operation of this prototype wind turbine.

Wind/Diesel Hybrid Powerplants

Electricity generated by wind energy can be less expensive than diesel generation. More than 800 diesel sets, with an aggregate rating exceeding

600 MW, generate electricity in remote Canadian locations isolated from main grid networks. Connecting wind turbines to diesel generators has the potential for significantly reducing fuel consumption. According to a study by Ottawa-based Mechron Engineering, the technique of cycle charging could, if teamed up with a wind turbine, reduce diesel fuel consumption by as much as 45% in a 50- to 100-kW system.

In cycle charging, the diesel and wind turbine would charge batteries and would not directly respond to the demands of the electrical load. The advantage of this approach is that it allows the diesel generator to run at peak efficiency when charging the batteries, which provide electricity to the community. The wind turbine would also charge the battery, sharing this duty with the diesel engine and reducing fuel consumption.

However, controls for such a hybrid wind/diesel powerplant, which must take into account a variety of new parameters, remain to be fully developed.

Following small-scale experiments on the Toronto Islands, NRC contributed a 50-kW vertical-axis wind turbine — de-rated to 37 kW by reducing rotational speed — to a major demonstration of a wind/diesel system in Sudbury, Ontario (see Figure 17). Indal Technologies provided the two 50-

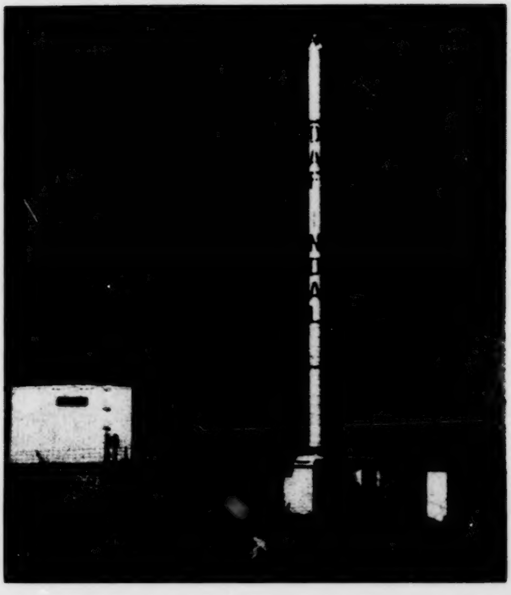
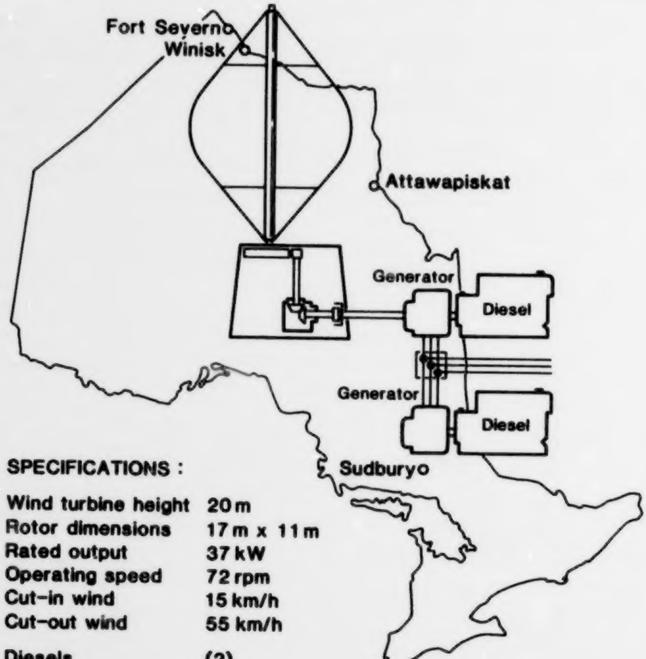


Figure 17 The 37-kW wind/diesel demonstration project at Sudbury, Ontario

kW diesel generators, while the Ontario Ministry of Energy contracted Indal to do the system engineering, prepare the site, and operate the system during test. Ontario Hydro acted as project manager.

The demonstration had two phases. In the first, the wind turbine was mechanically coupled to one of the two diesel generator sets (see Figure 18). The advantage of such a linkage is improved system efficiency and avoidance of a separate generator for the wind turbine. The alternative arrangement involves electrical connection of the diesel and wind turbine outputs, much the same as grid coupling.

The Sudbury demonstration indicated that substantial fuel savings were possible, but that mechanical coupling could only be justified when a new



SPECIFICATIONS :

Wind turbine height	20 m
Rotor dimensions	17 m x 11 m
Rated output	37 kW
Operating speed	72 rpm
Cut-in wind	15 km/h
Cut-out wind	55 km/h
Diesels	(2)
Rated output	2 x 50 kW
Operating speed	1200 rpm

Figure 18 Wind/diesel hybrid

This diagram depicts a wind turbine in Sudbury, Ontario, that was mechanically coupled to a diesel generator.

diesel generating system was being installed. Existing powerplants are not usually located on tops of hills where the wind regime is best; siting the wind turbine in the poorer wind regimes near such diesel generating sets would be uneconomic. However, in the electrical coupling mode the wind machine can be placed in a more favourable wind regime farther from the diesel generating sets. The wind turbine drives its own generator, which is autosynchronized with the diesel generator set. Such a hybrid system can reduce fuel costs by as much as 40%.

A major constraint in designing a wind/diesel system is that a diesel engine should not run for long periods at a small fraction of its rated power. Thus, if wind-generated power approaches the load demand, then the energy produced by the wind turbine may have to be dumped to allow the diesel generator to run above its minimum allowable power. To resolve this problem, the wind turbine can be made to generate electricity by itself, providing it does so at carefully controlled grid frequencies and voltages. In the Sudbury demonstration, the control system was redesigned to permit the wind turbine to operate in such a "stand-alone" mode and it produced power that met Ontario Hydro standards. A computer system controlled the rotor speed by varying the simulated electrical demand of a small community, preventing the rotor from generating unacceptably high or low frequencies.

Another option now being considered is adding energy storage capacity to the hybrid wind/diesel system. Excess wind power could be stored for seconds, or minutes at most, and then fed back to the load, thereby reducing diesel running time and eliminating wasteful dumping of energy. The type and capacity of energy storage and the overall control of the wind-diesel-storage system are currently being investigated in many countries, reflecting the attractive near-term markets for such technology.

Horizontal-axis Water Pump

At the turn of the century windmills that pumped water were a common sight. The multiblade horizontal-axis windpump was displaced from North American farms by cheap and convenient electric power. Now, windpumpers are starting to make a comeback. Calgary-based DELTX Windpump Corp. has manufactured an innovative low-speed windmill based on the delta-blade concept.

After testing of a 3-m model rotor in an NRC wind tunnel, to date two prototype windpumps have been built — the 6-m diameter WP-20 and its bigger 16-m WP-50 counterpart. The latter can pump water at a rate of 91 000 L/min (at a 9.1-m lift) when the wind speed is 13.3 m/s. The 16-

m-wide rotor rotates at 7 to 30 rpm. According to DELTX, this wind turbine is comparable to a 350-kW-rated wind electric turbine driving an electric pump. The company says the Windpump 50 can reduce energy costs by 10–30% (see Figure 19).

DELTX foresees a number of potential domestic and export markets: irrigation pumping, lifting large quantities of liquid from marginal oilwells to recover relatively small amounts of oil, pumping and aerating coarse sewage, retrieving municipal water from rivers and wells, and pumped storage hydroelectric systems.

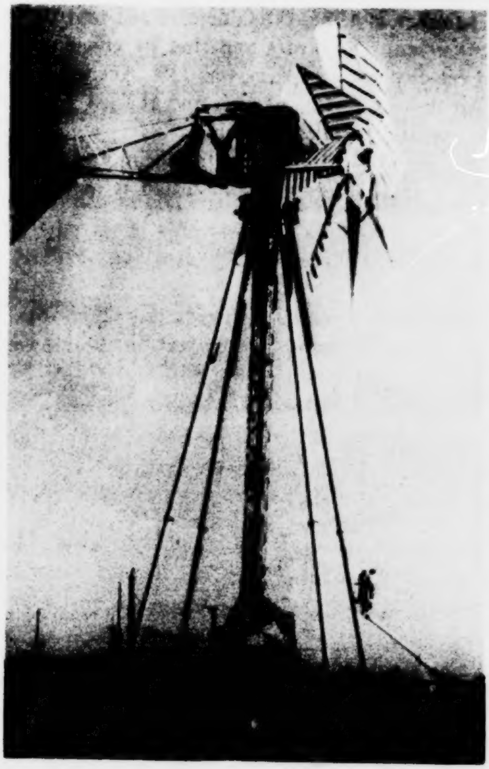


Figure 19 The WP-50 wind driven water pump manufactured by DELTX Windpump Corp.

The "Damp" Darrieus

Air is a fluid that is 800 times less dense than water and, consequently, many of the factors that determine good wind turbine design also apply to water turbines. Nova Energy Ltd., Dartmouth, Nova Scotia, has designed a vertical-axis hydraulic turbine based on technology from NRC's Darrieus wind turbine and the Bras d'Or hydrofoil project.

The "damp" Darrieus, as some have nicknamed it, has three blades instead of two and they are straight rather than curved. This machine had a rotor 2.4 m in diameter and each of the three blades was 1.5 m long and 0.2 m wide (see Figure 20). Tested in the St. Lawrence River at Cornwall, Ontario, in the summer of 1983, NRC determined that its rotor power was 4 kW in a river current of 1.6 m/s and that its efficiency, based on rotor frontal area and velocity just upstream, was 33%. According to NRC hydraulic specialists, fast-flowing water, 1.5 m/s and at least 3 m deep, is required for the economic operation of such a turbine.

The technology may be better suited for ocean and tidal currents; Nova has already built a small prototype and tested it in the Gulf Stream off

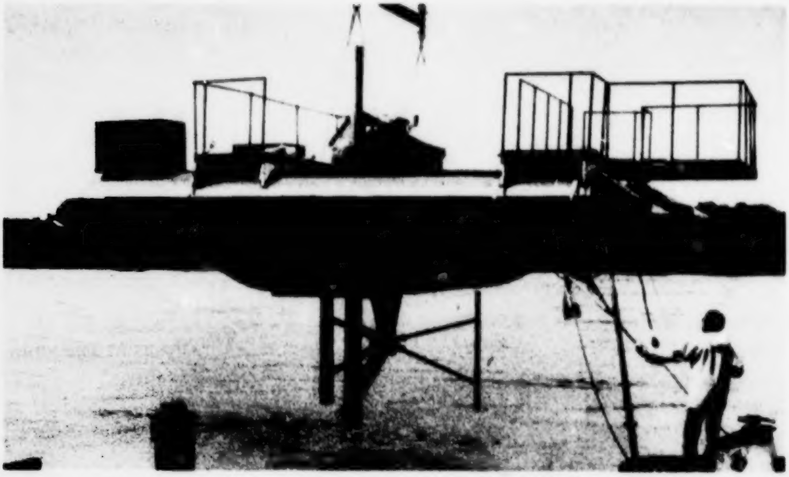


Figure 20 Hydraulic Darrieus turbine

A vessel containing the "damp" Darrieus water turbine is seen here being lowered into the water. The three-bladed turbine, based on the vertical-axis wind turbine, is visible at the bottom of the vessel.

Florida. This is a graphic example of how research focused on one technology can significantly aid the development of another technology — an important feature of the interrelation of programs within the Division of Energy of NRC.

Economic Prospects for Wind Energy

Specialists at the Department of Energy, Mines and Resources estimate that the current installed electrical generating capacity of wind turbines in Canada is 1.4 MW, although the commissioning of ÉOLE and other demonstration projects (proposed or underway) could increase this figure to 10–12 MW by 1990.

In the near future, the best market opportunities for wind energy will be found in remote communities and industrial sites. As noted previously, more than 800 diesel generators, representing a total power rating of 600 MW, now operate in such locations. A paper, which was presented by EMR to the 1985 Canadian Wind Energy Association Conference, concludes that wind-generated electricity can be cost competitive with diesel-generated electricity. This would hold true for a wide range of stand-alone wind turbines if the price of diesel fuel is higher than 50¢/L and the annual average wind speed exceeds 5.6 m/s.

The same paper also concludes that, in most cases, electricity generated by wind turbines cannot compete with the price of grid electricity generated by Canadian utilities, especially in the large markets of Quebec and Ontario. Given the relatively specialized market for wind turbines in remote Canadian locations, the Canadian wind turbine manufacturing industry will have to depend, in the short term, on the export market to augment economies of scale and production volume to improve cost effectiveness.

Computing the cost of wind-generated electricity depends on a large number of factors, many of which vary from site to site. These include the wind regime, power output of the wind turbine per square metre of swept area, the installed cost of the system, interest rates, expected life of the wind turbine, and operating and maintenance costs.

An NRC technical memorandum, *Assessment of Performance and Cost-effectiveness of Wind Energy Conversion Systems*, provides a simplified method for quickly determining the likelihood that a wind turbine will perform economically. Figure 21, taken from this document, summarizes the economic factors that must be taken into account. The dramatic effects of annual average wind speed can be clearly noted.

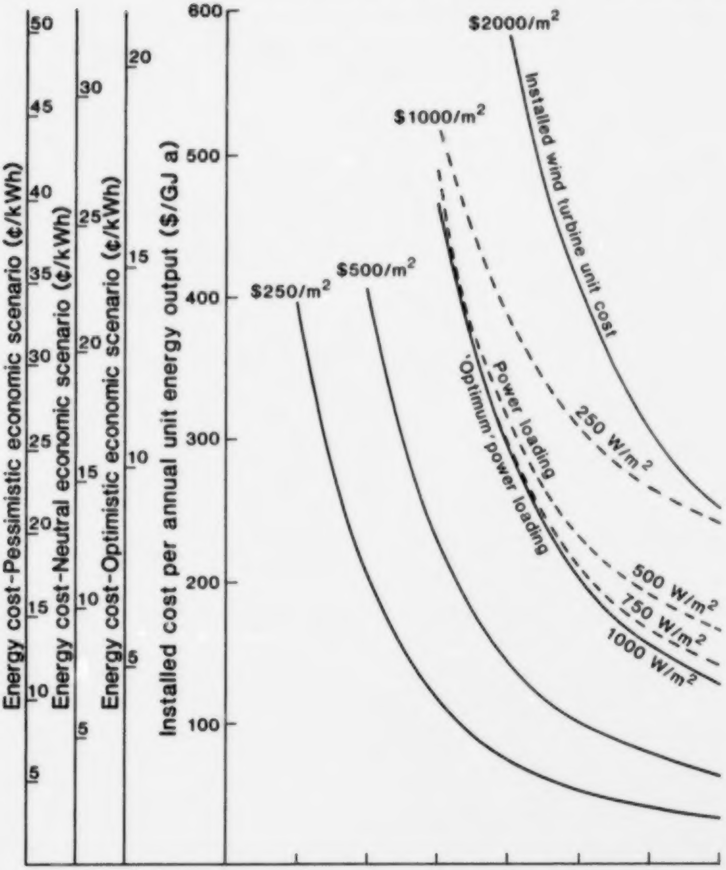


Figure 21 Determining the economic viability of installing a wind turbine

Key factors that determine the economic viability of a proposed wind turbine installation are shown in Figure 21. Consider a wind turbine rated at 15 kW, with a 25-ft-diameter rotor, and costing $22 000 at the factory. The proposed site has an annual average wind velocity of about 6 m/s. The installed cost of the wind turbine is estimated at $38 500 (factory cost times 1.75). The swept area is computed to be 45.6 m². The unit cost of the installed wind turbine is computed by dividing the estimated installed cost by the swept area (38 500/45.6 = 329 $/m²).

The power loading is acceptable for a wind regime of 6 m/s and the plot also shows that the estimated installed cost is equivalent to about $390 GJ/a. The resulting cost of energy ranges from 13.5 to 33¢/kWh, depending on assumptions made about the wind turbine operating life, operating and maintenance costs, and interest rates (factors included under the economic scenario category). If this site were served by an electrical utility, the wind energy system would not be an economic proposition since electricity in most parts of Canada costs less than 8¢/kWh. But the wind turbine might well be economic compared to diesel generators using high-priced fuel.

Recommendations

Regarding wind energy systems, it is recommended that:

1. Wind energy research and development in Canada should continue to emphasize intermediate-scale vertical-axis wind turbines for electrical generation and focus on improving reliability and cost effectiveness.
2. Comprehensive analytical and experimental system engineering studies should be performed to establish the primary criteria and optimum operating parameters for wind/diesel powerplants which incorporate energy storage for delivering improved quality of power at lower cost.
3. A concentrated effort should be made to demonstrate Canadian wind turbine technology through selected wind farm and autonomous wind/diesel installations.
4. Continued development and evaluation of delta-bladed windpumps should be accelerated to confirm performance and reliability. Concurrent studies should be made to examine alternative materials and fabrication techniques appropriate to developing countries.
5. Analytical techniques should be improved and extended to provide better design tools for wind turbine manufacturers, especially with regard to structural dynamics, fatigue life assessment, control and protection approaches, and system/site optimization.

4 BIOENERGY

Description of Bioenergy Technology

Although the term bioenergy is a relatively new one, man has been exploiting the energy content of wood, animal manure, and crops such as straw for thousands of years, mainly through direct combustion.

These "lignocellulosic" materials, or biomass, contain three basic components:

- cellulose, a fibrous carbohydrate ($C_6H_{10}O_5$) which is the chief substance of plants and is used, for example, in manufacturing paper
- hemicellulose, which constitutes about one quarter of the matter in trees and is composed of polysaccharides
- lignin, a complex organic material which, mixed with cellulose, acts as a glue that strengthens the cell walls of plants and gives them their structure

Chemically, biomass is essentially carbon, hydrogen, and oxygen and can be considered a stored form of solar energy, since it is the product of photosynthesis — the process by which plants produce carbohydrates from atmospheric carbon dioxide and water in the presence of sunlight.

Today, technology can convert biomass into a variety of energy forms. Gasifiers produce low- to medium-energy synthesis gases from wood and these gases can be burned to produce heat, power an electrical generator, or serve as a feedstock for the production of methanol fuel (CH_3OH) and other chemicals.

Anaerobic digesters, on the other hand, convert animal manure and organic industrial wastes into biogas (largely consisting of methane) for heating buildings or power production. As well, of course, crops containing starch and sugars can be fermented by microbes to produce fuel ethanol (C_2H_5OH).

At the R&D level, modern bioenergy encompasses a wide range of scientific and technical activities. These include developing computer models to aid in determining the extent of a nation's total forest biomass resource, the genetic manipulation of microbes for increasing the yield of fermentation processes, and the exploration of economic ways for utilizing all the basic lignocellulosic components.

One of the most important developments in recent years has been a push by the international science and technology community to devise economic means to separate, or fractionate, lignocellulosics into their three basic components without greatly damaging their structures. If successful, this R&D could have a substantial impact on energy and chemical markets. The fractionated cellulose, for instance, could be hyrolyzed (decomposed) into sugars — by acid or enzymes — and fermented into ethanol. The hemicellulose could be used to produce chemical solvents. Drugs, resins, and adhesives could be manufactured from the long-chain lignins. In this way, virtually all of the biomass would be converted into commercial products.

Program Rationale and Background

The economic viability of exploiting energy from biomass drew the strong interest of federal policy makers in the mid-1970s, amid forecasts of high oil prices, as discussed in Chapter 1.

The government considered many bioenergy options, including the conversion of wood into methanol. Another alternative, however, proved more attractive in the short term. In March 1977, a government/industry Advisory Panel on Wood Energy held a meeting that examined the fuel needs of the forest products industry, which then consumed 7% of Canada's primary energy. By substituting oil and gas with waste biomass, this panel reasoned, the forest industry could, over time, become largely energy self-sufficient.

The views of this panel led to a milestone EMR report, *Tree Power: An Assessment of the Energy Potential of Forest Biomass in Canada*. The introduction noted that, in 1974, the forest products industry generated 8.2×10^6 t of surplus materials with a recoverable energy of 94×10^{15} J (assuming 65% conversion efficiency). Moreover, the report also estimated that 1000 to 2000 wood-fired boilers already existed in North America and further pointed out that wood gasifiers were very close to commercialization.

While enthusiasm for the methanol option remained strong, particularly when viewed from a longer-term perspective, the availability and economics of combustion and gasification technologies favoured policies that would initially encourage substitution for oil and gas in the forest products sector. Furthermore, much of the industry was dominated by a handful of large firms, most of them possessing considerable experience in implementing process technology. Changing the energy consumption practices of a relatively few players could have a substantial impact on national oil and gas consumption.

In 1978, the federal government introduced two major bioenergy programs: the Forest Industry Renewable Energy Program (FIRE), which contributed up to 20% of the capital costs of a bioenergy conversion project in the forestry sector, and the Energy from the Forest Program (ENFOR), which provided wide-ranging technical support for commercial and development work in forest energy applications.

Both programs turned out to be very successful. By 1980, Forest Industry Renewable Energy projects totaling $32 million were approved and would lead to the displacement of 25 PJ/a of fossil fuels, an impressive figure considering that the energy value of Canada's net annual oil imports in the early 1980s was about 210 PJ. Because of this success, Forest Industry Renewable Energy grants were extended to other businesses and institutions. The 1986 goal was to replace fossil fuels having an energy value of 116 PJ/a. It was estimated that this would cost $196 million to achieve.

The Energy from the Forest Program had a much more modest budget, initially $29 million over a seven-year period, but its scientific and technical achievements — many of which continue to attract world-wide attention — were numerous and significant. Hardly an area of bioenergy was left untouched by the Energy from the Forest Program. Among other things, it funded a comprehensive forest biomass inventory, environmental research, the setting of standards for wood-fired industrial boilers and residential wood stoves, development of tree harvesting and wood handling technology, silviculture projects, and research projects covering virtually all steps involved in converting biomass into gaseous or liquid fuels.

While forest biomass projects received considerable financial support in Canada, agricultural biomass had a much lower profile. Before the 1973 oil shock, Agriculture Canada had studied the possibility of converting grain into ethanol, motivated largely by low grain prices due to over-production. This option never gained the generous subsidy support it was to receive later in the United States.

In evaluating agricultural energy consumption, it was observed that farms themselves consumed only a small portion of the energy required in food production, the heavy consumption occurring in flour mills and other kinds of processing plants. Exploitation of agricultural biomass stressed the conversion of animal wastes and plant residues into biogas, thereby also attacking a pollution problem that plagued large farms, feedlots, and processing plants alike (the latter being concerned with wash water wastes that encourage the proliferation of oxygen-consuming microorganisms in water). After some initial disappointments, biogas production technology underwent a series of significant improvements, notably in NRC laboratories, and is now being widely implemented.

National Research Council Role in Bioenergy

Within the total interdepartmental effort, NRC's bioenergy R&D goals were aimed at improving biomass fractionation, selecting and genetically manipulating microbes to assess their potential in producing fuels and chemicals, examining techniques for promoting the fast growth of certain tree species, and developing integrated, mechanized systems for operating tree energy plantations.

International Status of Bioenergy Technology

Leading Countries and Performers

Despite Canada's vast biomass resources, this nation was not in the forefront of bioenergy science and technology when the cost of oil started to escalate in the early 1970s. That distinction belonged to two other nations, Sweden and the United States.

In the Swedish forestry sector, companies strove to become as energy self-sufficient as possible by utilizing tree residues. Elsewhere in the country, boilers of existing district heating systems were switched from fossil fuels to wood wastes, while numerous other communities were converted to wood-based district heating. Sweden also undertook a large-scale tree growing program and developed expertise in short rotation forestry plantations.

Across the Atlantic, the United States called on its formidable R&D infrastructure to explore every promising facet of bioenergy technology. Besides an ambitious R&D effort, the federal government and some state governments launched subsidy programs to support conversion of corn into ethanol for use in gasoline blends (10% ethanol, 90% gasoline).

The subsidy consisted of a 10% energy tax credit for construction of ethanol-from-biomass plants, the waiving of the federal tax that applies to gasoline (5¢/gal) and, in some cases, the waiving of state gasoline taxes (ranging from 3.5¢ to 11¢/gal). A 9¢ tax waiver on a 10% blend translated into a 90¢ subsidy for a gallon of ethanol.

The subsidy program has had a great impact on a number of fronts. For instance, almost all ethanol in the United States is now produced from corn, rather than from ethylene manufactured in petrochemical plants.

Lipinsky and Shepherd, in a paper presented at the Fifth Canadian Bioenergy Seminar, predicted that fuel ethanol usage in the United States could, given favourable corn prices, exceed 1 billion U.S. gallons (vs. 444 U.S. gallons in 1983) and provide the equivalent of about 1% of the American gasoline supply. This would require 3% of American corn production, possibly increasing corn prices by 6–10%.

Members of the European Economic Community (EEC) have come to view bioenergy as a means of dealing with massive agricultural surpluses and the associated cost of subsidizing this production — $14 billion in 1983. Key bioenergy projects are being built to extract both the food and energy value of crops, but the EEC is also thinking of designating some farm land for growing energy crops. Such a move could, to cite one example, drastically reduce dairy surpluses by removing milking cows from the land.

Research Agreements and Collaboration

Canada's participation in international bioenergy R&D programs was, at the government level, largely carried out through two agreements with the International Energy Agency. The Biomass Conversion Technical Information Service (BCTIS) provided abstracts of reports and other reference material, as well as studies dealing with specialized topics relating to bioenergy. The second agreement dealt with forest energy and concentrated on three key areas: short rotation forestry, harvesting and collection of forest biomass, and biomass conversion technologies.

Strong informal links were also developed with the EEC biomass program. Canadian experts took part in closed-door meetings and were also invited to speak at conferences. This encouraged the flow of technical information that benefited both sides.

Although the EEC program did not emphasize forest biomass, it provided strong support for developing improved technology to gasify agricultural wastes and the anaerobic digestion of animal and food wastes.

As for less-developed countries, Canadian participation was directed with the help of the International Development Research Centre (IDRC) and the Canadian International Development Agency (CIDA). Education and consulting services, arranged on a country by country basis, were the main assistance vehicles.

The IEA agreements gave Canada a valuable window on technology, encouraged the transfer of technology among the participating countries, and allowed the pooling of considerable scientific talent to tackle significant R&D projects. As a general rule, the further a project was from the marketplace, the greater the cooperation. Canada and Sweden, small nations by world standards, were able, for example, to mount a highly effective partnership in short rotation forestry. However, in forest machinery and gasification, where the scent of commercial markets was strong, the leading players tended to go their own ways.

The Status of Bioenergy Technology in Canada

The past decade has witnessed a massive national research, development, and demonstration effort in bioenergy that has had a significant impact on Canadian energy supply and demand. While overall domestic energy production increased 10.2% between 1974 and 1984, bioenergy production during the same period increased from just over 200 PJ/a to more than 500 PJ/a and is expected to reach 1000 PJ/a in the year 2000. By comparison, the maximum output of the Syncrude oil sands plant is 275 PJ/a.

As these figures indicate, the application and development of technology has played a vital role in bioenergy. During the past decade, Canada went from a position of weakness in bioenergy science and technology to one of leadership in many fields. This reflects, in large part, the $200 million the federal government invested in various bioenergy activities between 1975–76 and 1984–85.

Combustion

Financial assistance from federal government programs has played a vital role in the development of wood combustion technologies, particularly those intended for use in the forestry sector. In some cases, this assistance enabled important new products to be brought into the marketplace.

The Forest Industry Renewable Energy and the Energy from the Forest programs were instrumental in commercialization of the Wet Cell Burner, developed by Lamb–Cargate Industries Ltd. of New Westminster, British Columbia. The Wet Cell processes 3–10 tons of moist wood fuel per hour (see Figure 22).

The burner employs two-stage combustion, involving, first, the pyrolysis of wood fuel and then, in a second stage, complete combustion of the resulting gases in a cyclonic combustion chamber. The result is a clean hot gas that can be used in drying kilns.

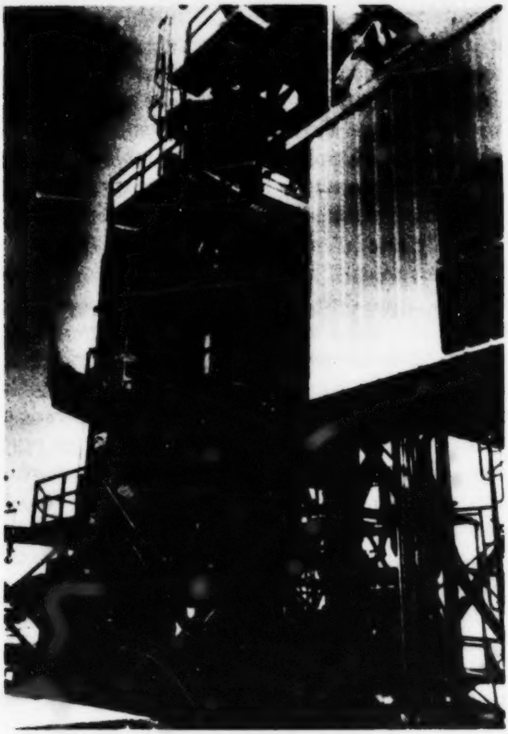


Figure 22 Lamb–Cargate's Wet Cell Burner at a sawmill in British Columbia

A sawmill in British Columbia, which installed the Wet Cell at a cost of $2 million, saved the equivalent of 7400 m^3 of oil per year, reduced its waste disposal problem, and was able to comply with provincial air quality standards. Lamb–Cargate is also selling its Wet Cell Burner in export markets.

Another important contribution in promoting forest waste as a fuel came from a program to test wood-fired boilers and involved the Canadian Boiler Society. This program increased understanding of combustion dynamics and led to improvements in materials handling, combustion performance, and emission control. Tests done on two upgraded wood-fired boilers demonstrated that fuel costs in such boilers would be $1 million lower per year than in oil-fired boilers.

Meanwhile, in the residential sector, the setting of safety, efficiency, and emission standards for wood stoves and other wood-burning appliances established consumer confidence in this technology and proved valuable in promoting sales.

By 1984, primarily through combustion of wood wastes, the forestry sector consumed biomass energy totalling 400 PJ/a, while residential wood-burning appliances produced 100 PJ/a.

Wood Pelletizing

Shell Canada Ltd. was among the first companies to see the profit potential of bioenergy. It bought a licence for an American process that turns wood wastes into pellets 6 mm in diameter and 12 to 24 mm in length. A subsidiary, Bioshell Inc., was formed to exploit the technology.

Bioshell now operates three plants, including one in Hearst, Ontario (the others are in Iroquois Falls, Ontario and Lac Megantic, Quebec). Their construction was partially supported by Forest Industry Renewable Energy program grants. At the Hearst plant, 800 t of wood wastes, containing 50% moisture, are trucked in daily from six neighboring sawmills. These mill wastes are ground to uniform particle size, dried, and formed into 350 t of pellets (see Figure 23). Every day, several truck loads of pellets are transported to boilers of a nearby Abitibi Price Co. newsprint mill. This has saved the company $1 million in annual fuel costs.

Figure 23 The Bioshell process which converts wood wastes into fuel pellets for boilers

Wood Gasification

In the early 1980s, Levesque Plywood Ltd. in Hearst, Ontario, invested more than $2 million in the demonstration of what was then Canada's largest wood gasification system (see Figure 24). Designed by Omnifuel Gasification Systems Ltd. of Toronto, the fluidized bed combustion system was built to counter the increasing cost of natural gas in drying applications and the expense of disposing of large quantities of wood waste.

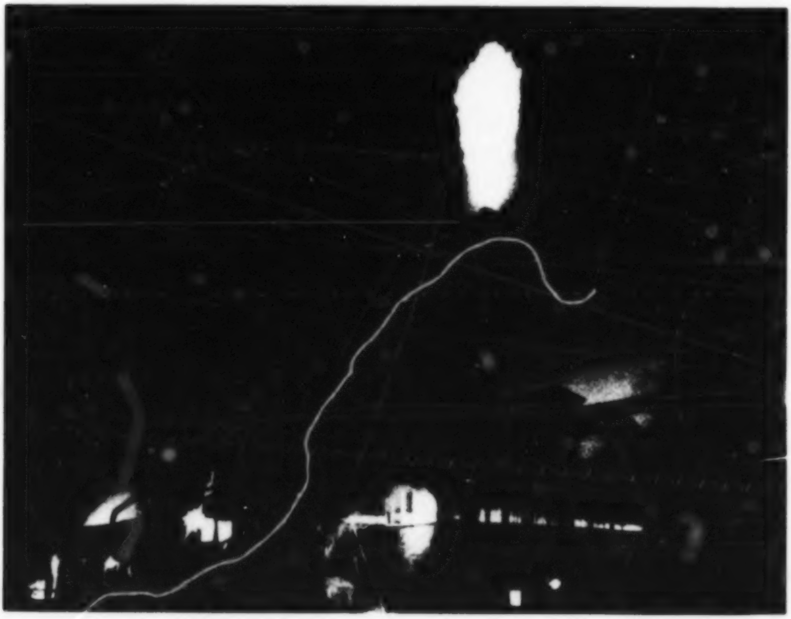


Figure 24 Fluidized bed gasifier manufactured by Omnifuel Gasification Systems Ltd.

As much as 5 t of sawdust and wood chips per hour could be fed into the Hearst gasifier by an air-tight screw conveyor system. At the bottom of the gasifier, which measured 3 m in diameter and 12 m high, a bed of sand was agitated by a stream of blown-in air. This caused wood and sand to bubble vigorously. A start-up burner provided the initial heat for combustion and was then shut off. The temperature inside the gasifier could reach 800°C. (See Figure 25.)

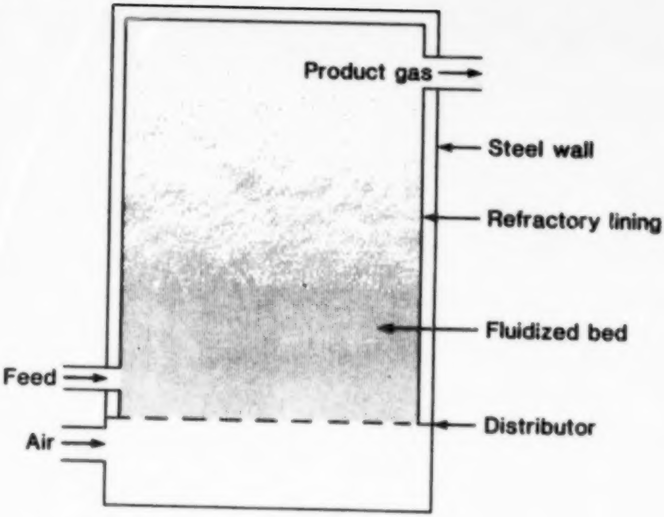


Figure 25 Simplified sketch showing the operation of a fluidized bed gasifier

Omnifuel's fluidized bed gasifier is also a main element of the Biosysn wood gasification project, one of the most ambitious of its kind in the world. It cost $11.5 million to construct the plant in Quebec's Montmagny district (see Figure 26), while the demonstration phase will add a further $10.1 million in expenses. Biosyn is financially supported by Nouveler Inc. and the federal and Quebec governments. Nouveler has also teamed up with SNC Inc., a Montreal-based engineering company, to form Biodev International Inc., which is using Biosyn technology to develop electrical generating systems for less-developed countries.

Completed in 1985, the Biosyn plant can gasify 10 t of dry wood an hour, using oxygen as the fluidizing agent. The design pressure is 1.7–2.0 MPa (17–20 times atmospheric pressure), while the design temperature is 850°C. Also, part of the plant is a system for handling, shredding, drying, and storing wood residues. Much of the plant's operation is computer controlled.

The plant is designed to produce 16 t/h of synthesis gas, which could be converted into 55×10^6 L/a of methanol. The raw synthesis gas is composed of 25–35% CO, 8–20% H_2, 15–20% CO_2, 10–20% C_xH_y, and 15–30% H_2O.

The gasifier units are soon expected to attain 6000 to 8000 h of reliable operation annually, meeting industrial performance standards for combustion

Figure 26 Biosysn wood gasification project

systems. The demonstration of a reliable gas cleaner, which removes and recycles carbon from the raw synthesis gas, is expected soon.

Anaerobic Digestion

Canada is a world leader in anaerobic digestion technology, which transforms animal and biological industrial wastes into methane, animal feed, Single Cell Protein, or fertilizer. Although the overall production of energy from anaerobic digestion is not expected to be substantial in the near term, it effectively deals with bothersome environmental problems, notably foul smells and water pollution. Therefore, the technology is expected to find increasing application.

Demonstrations of large anaerobic digestors, undertaken by Agriculture Canada in the late 1970s, proved less than satisfactory, but they did indicate what developments were needed to produce a workable technology. An anaerobic digester designed by NRC, known as the Downflow Fixed Film Reactor (DFFR), provided a breakthrough.

Based on NRC's work, Maclaren Engineers Inc., London, Ontario, built a large-scale, $200 000 anaerobic digestion system in 1983 to treat hog wastes on a farm in southwestern Ontario. A key feature of this digester, which has a volume of 45 m^3, is the vertically aligned plastic tubing having mechanically roughened surfaces with 40 grooves per centimetre (see Figure 27). Microorganisms that convert the waste into methane can fix themselves to these grooves and avoid being washed away as the hog effluent moves through the reactor. Every cubic metre of solution in the reactor is in contact with 100 m^2 of surface area, ensuring that the material is readily accessible to microbes.

Depending on feed rates, daily biogas production varies from 35 to 100 m^3. The discharged biogas, which normally contains 65% methane, is cooled, stripped of moisture and particulate matter, metered, and stored. The biogas fuels a 15-kW propane/biogas generator that produces electricity and waste heat.

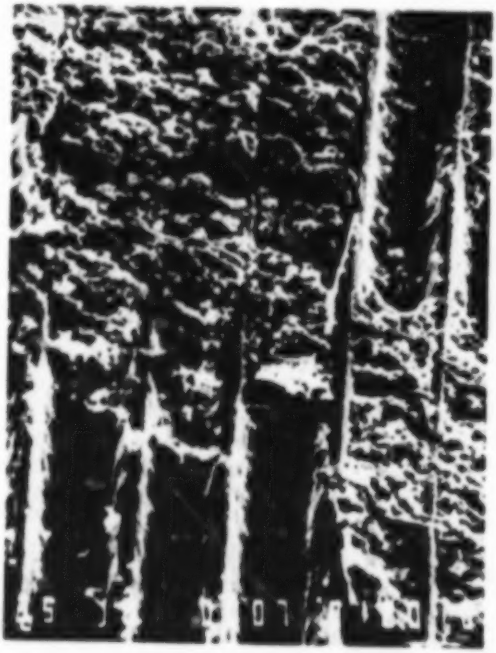


Figure 27 Microphotograph of anaerobic bacteria

This electron microscope photo shows anaerobic bacteria attached to grooves in the plastic tubing of the Downflow Fixed Film Reactor designed by NRC. The grooves are produced during the manufacturing process and play an important role in the reactor's effectiveness. They help prevent the bacteria from being washed away as material moves through the reactor.

Protein can also be recovered at two points in the treatment process, reducing feed costs. Maclaren estimates that the payback of a hog waste treatment system for 150 animals is seven years, without accelerated tax writeoffs for energy-related equipment.

Besides Maclaren, three other firms are commercializing NRC's anaerobic digestion technology in Canada and abroad: Canviro Consultants Ltd., Kitchener, Ontario; ADI Ltd., Fredericton, New Brunswick; and PH-Tech, Levis, Quebec.

National Research Council researchers, meanwhile, are now probing the molecular processes and structure of microorganisms. Their investigations may provide clues to developing highly efficient and hardy bacteria for anaerobic digesters. One area of interest is a branch of archaebacteria known as methanogens, which can exist in boiling acids, smoldering coal tailings, and saturated brine.

Biomass Pre-treatment Technologies

An important goal of bioenergy R&D in Canada has been to develop low-cost processes for fractionating lignocellulosics such as wood and straw into their three, basic components: lignin, hemicellulose, and cellulose. Successfully developing such pre-treatment processes would have a major economic impact.

Pre-treatment technology could enable companies to extract fibre, food, fuel, and chemicals from wood pulp, a development that has major implications for the pulp and paper industry. The era of the Bioplex, or biomass refinery, may emerge. In short, a major technological opportunity exists for new biomass-based industries.

Canada has developed considerable technical expertise in lignocellulosic fractionation. The National Research Council, Forintek, the British Columbia Research Council, and a number of universities (notably the Universities of British Columbia, Waterloo, and Sherbrooke) have all received federal R&D funding towards further developing the basic technology.

On the commercial front, several firms are internationally known for their pre-treatment processes. Among them is Stake Technology Ltd. of Oakville, Ontario, which has developed a pre-treatment steam cracking system for separating lignocellulosic residues into their three basic fractions.

Several years ago the firm began marketing a steam hydrolyser that breaks the bond between lignin and cellulose, making it possible for cattle and other ruminants to digest the cellulose in wood chips, bagasse, and straw. In the Stake process, biomass is continuously fed into a pressurized steam vessel and exposed to saturated steam at temperatures ranging from 180 to 220°C for 3–60 min. Stake is also supplying the pre-treatment facility for the Soustons Project in France. This complex is to convert straw residue into sugars and lignin, which will then be made into ethanol and Single Cell Protein.

Iotech Corp. of Ottawa is marketing a steam explosion process for fractionating lignocellulosics. This thermomechanical process rapidly heats wood chips in a sealed vessel and then explosively releases a mixture of fibre and steam through a nozzle. Iotech and Monenco Ltd. have built a $5 million pilot plant that employs steam pre-treatment and a proprietary enzyme-based hydrolysis process to convert wood into a feedstock for ethanol production.

On another front, St. Lawrence Reactors of Mississauga, Ontario, is using federal and provincial R&D support to develop a continuous acid hydrolysis process to produce ethanol from corn starch and lignocellulosics.

Biomass Resource Inventory

When bioenergy policy was being formulated in the mid-1970s, the size and composition of Canada's total forest biomass was unknown, so wood's potential energy contribution could only be estimated. No reliable data existed that indicated how many tonnes of wood grew in this country and what amount could be used for energy.

The reason for this was that existing inventories classified only merchantable trees. Moreover, in determining tree volume, it was also the practice to measure just tree stems and not the discarded branches. Typically, the stem accounts for 60% of a tree's volume, although figures vary depending on tree species and age.

Since these inventories were designed to provide reliable data about the supply of pulpwood and sawlogs, they understandably excluded trees that would not be harvested. Thus, even within existing inventories many species of trees were bypassed and, on the larger national scale, a vast area of unmerchantable forest was never inventoried. As well, no one knew how much of Canada's forests could be accessed by roads and other transportation links, an important economic factor in exploiting wood energy.

It was for this reason that the Energy from the Forest program funded Canada's first forest biomass inventory. Compiled by the Canadian Forestry Service, in cooperation with provincial forestry agencies, the project involved the felling of 12 000 trees (comprising all major species in Canada). By weighing, measuring, and analyzing these trees, tree biomass equations could be derived for determining how many tonnes of oven-dried wood there were in a hectare of forest.

The stems of felled trees were cut into discs and their fresh weight recorded on site, with separate readings taken for wood and bark. Branches, including those with foliage, were classed according to their location on the tree and also weighed on site. Later, sample discs and branches were oven dried and weighed.

These data were then fed into the Canadian Forest Resource Data System, in which forest lands are divided into 50 000 summary units, or "cells." In addition to the inventory data, each cell contains information about the area of forest, access to transportation systems, and other relevant factors.

The forest biomass inventory yielded a number of important results. The total weight of trees in Canada exceeds 26 × 10^9 t, of which 79% is on productive forest lands. Furthermore, nearly two thirds of this wood can be accessed by an existing transportation system.

From an energy point of view, it is now reliably estimated that 54 × 10^6 t can be economically exploited annually — a primary energy content exceeding 1000 PJ, or about 18% of Canada's annual energy consumption.

Simulating Bioenergy's Environmental Impact

Computer simulation, an important tool in a variety of industrial and scientific applications, now also provides insights regarding the long-term impact of intensive forest management techniques on the soil, which may be eroded or suffer nutrient loss. This, of course, would affect the long-term productivity of forests.

The computer model in question, called *Forcyte*, was developed by researchers at the University of British Columbia. In 10 min of simulator time, this program can predict the outcome of 300 years of forest management. Now in its 11th version, the model consists of three compartments: plant biomass and nutrient content, soils, and available soil nutrients. *Forcyte-11* can simulate a number of forest management practices, such as prescribed stand burning and different re-planting methods (as well as natural events like insect tree kill) to predict how large trees will grow to be. It will also make predictions about the nutrient status of the soil and will, additionally, evaluate the economic performance and energy efficiency of alternative forest management practices.

Short-rotation Forestry and the National Research Council's Machinery Program

Ontario's Ministry of Natural Resources has been a world leader in developing hybrid poplars that grow 4 to 10 times faster than trees in a natural environment. By applying techniques of short-rotation forestry

(SRF), hybrid poplars can, within five years of their planting, reach a height of 10 m and an average stump diameter of 13 cm (see Figure 28).

Hybrid poplars are treated much like an agricultural crop and, indeed, short-rotation forestry is often referred to as agro-forestry. Trees are planted in neat rows and are generally harvested in 2-, 5-, or 10-year periods. But unlike agriculture, new machinery still has to be developed to bring the efficiency of energy plantations to the level of a well-run modern farm. The National Research Council undertook a program to help mechanize virtually all the operations of hybrid poplar plantations, everything from the initial preparation of the site to the delivery of the harvested wood to its final destination.

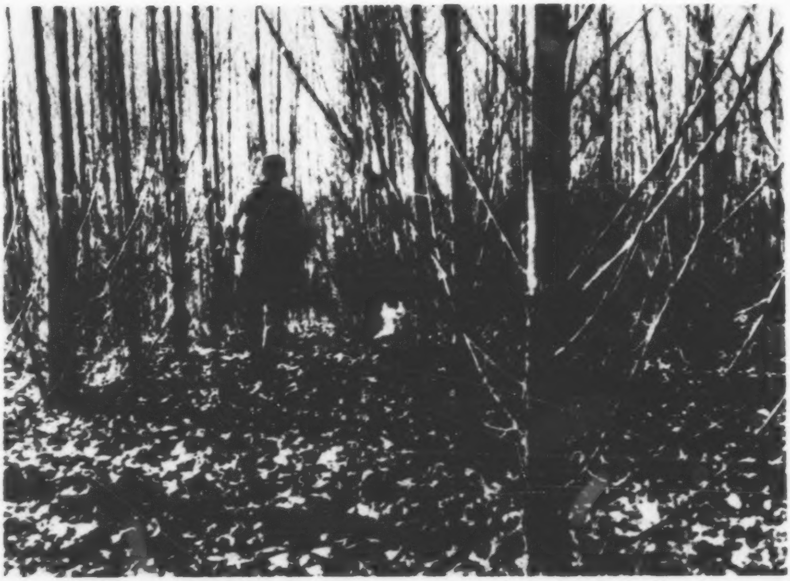


Figure 28 A forestry official amid fast growing 5-year-old hybrid poplars

Working with industry and other R&D groups in Canada, NRC investigated the design of several machines. This included a brush harvester for clearing growth on abandoned agricultural or forest land. The machine, which attaches to a farm tractor, cuts a 2-m-wide swath and has mechanical arms that continuously grab the cut brush (see Figure 29).

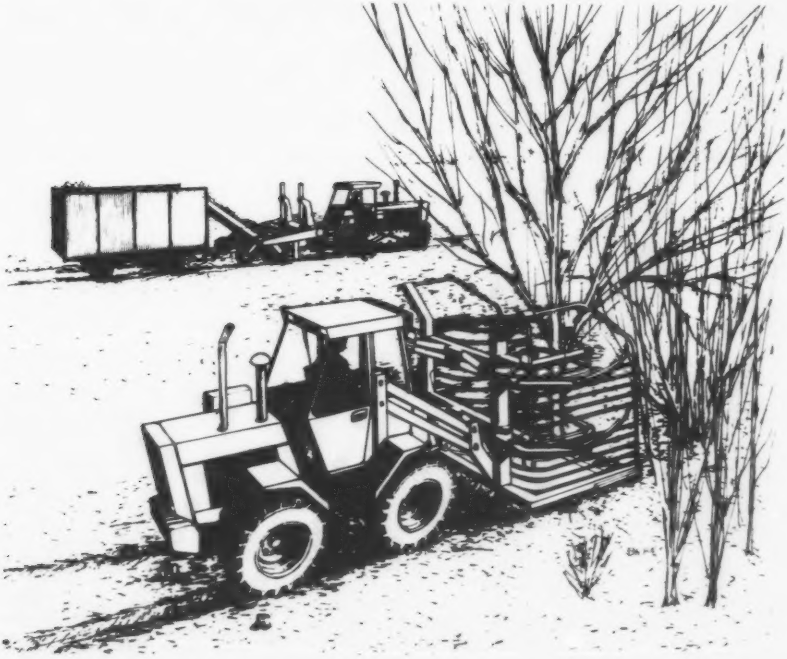


Figure 29 Brush cutter

For the nursery, development went ahead on a whip harvester, a device that cuts and collects bundles of 1- to 2-year-old nursery poplars (whips) for production of cuttings (see Figure 30).

An automatic planter being developed by NRC demonstrates how technically sophisticated some of these machines must be to function efficiently. It is equipped with eight robot arms which, in turn, have suction heads to pick up cuttings from the storage magazine and transfer them onto a conveyor. The cuttings are deposited into a slit in the ground produced by a disk. A microprocessor controls the robot arms to enable continuous operation at a ground speed of 2.5 km/h (see Figure 31).

The National Research Council also supported the development of machinery for harvesting 5- and 10-year-old hybrid poplars, which is an order of magnitude more difficult than harvesting corn. A 5-year-old hybrid poplar

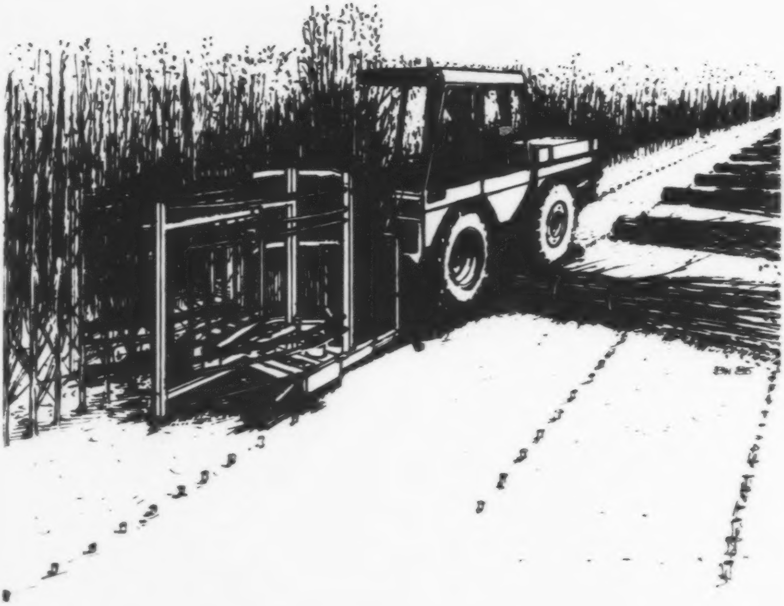


Figure 30 Whip harvester

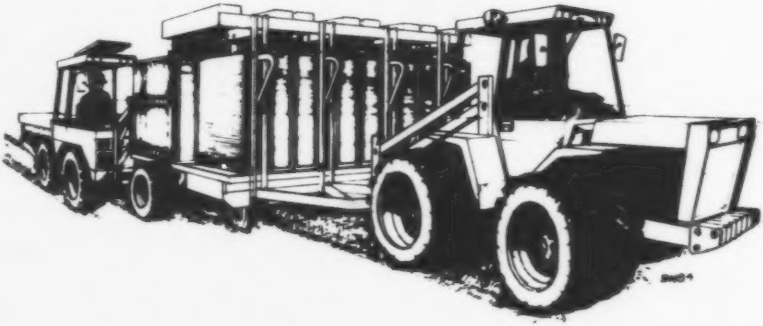


Figure 31 Automatic planter

weighs, on average, 32 kg, stands 10 m high, and has a stump diameter of 13 cm. A prototype harvester, or feller-buncher, was developed. It cuts the tree stump cleanly and bunches the trees in groups of 15, depositing them for later collection. This machine can fell and bunch 1000 trees per hour (see Figure 32).

When a poplar plantation is cleared the stumps sprout new shoots, known as coppice growth. The National Research Council is developing a coppice harvester that will be pulled by tractor. It will cut the shoots on one side with a reciprocating cutting saw and transfer them by conveyor to a chipper (see Figure 33).

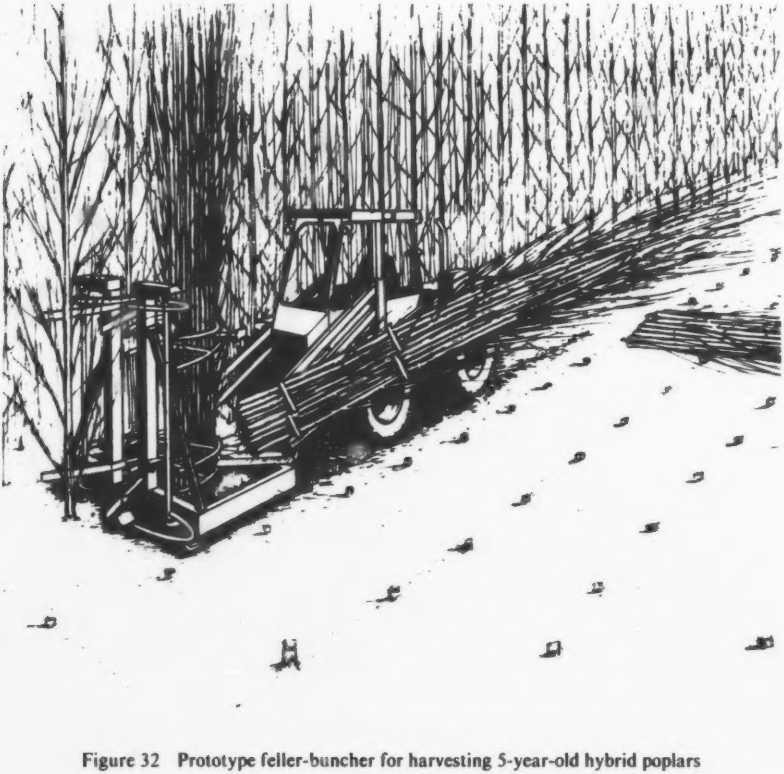


Figure 32 Prototype feller-buncher for harvesting 5-year-old hybrid poplars

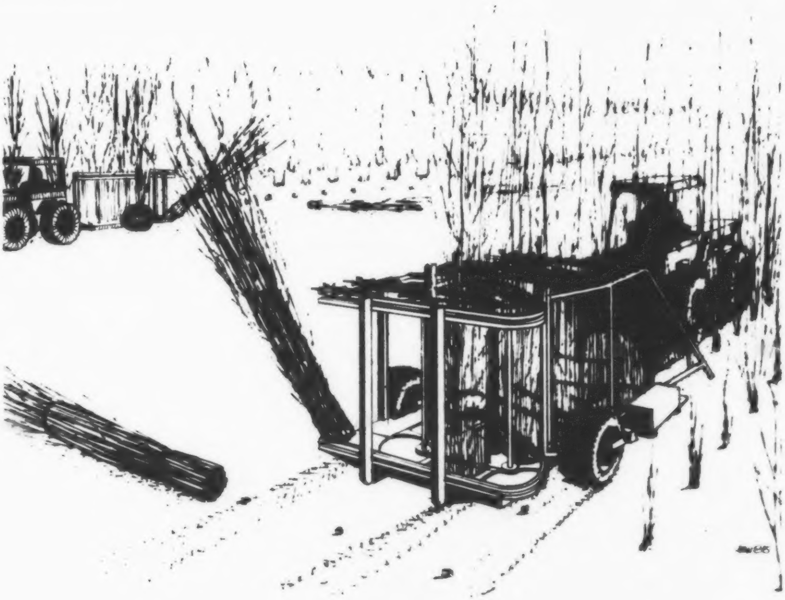


Figure 33 Coppice harvester

Economic Prospects for Bioenergy

In general, the prospects for bioenergy in Canada are favourable. In the forest sector, many companies now treat the decision to purchase systems for recovering energy from forest residues as they would any other major capital investment decision, thanks to the impetus provided by the Forest Industry Renewable Energy program. In fact, in terms of value, energy is the third most important product in this industry, so combustion technologies should continue to find increasing acceptance in the forest sector.

On the other hand, the prospects for the economic production of methanol fuel from wood do not appear to be economically viable in the short term, given the huge quantities of natural gas — widely used as a methanol feedstock — that now exist in Canada. As well, the world capacity for methanol production greatly exceeds demand at present, prompting the recent closure of a number of plants.

However, it could be argued that a considerably larger demand will exist for methanol by the early 1990s. Many countries are planning legislation that calls for the removal of lead from gasoline and this will increase the demand for octane enhancers like methyl tertiary-butyl ether (MTBE). Moreover, nations such as New Zealand are building plants that employ catalysts to convert methanol directly into gasoline.

What effect this will have on natural gas prices several years from now is still open to speculation. Given technological developments in wood gasification and other related fields, it may be that methanol from wood could become economically attractive in the 1990s.

Finally, one last point needs to be made regarding bioenergy's impact during the past decade. There are indications that bioenergy may produce an indirect and significant economic impact on the forest sector. This is because the economics of biomass energy are changing management perceptions of the forest resource.

For example, where previously only conifers were harvested for their fibre, some companies are now also harvesting scrub hardwoods for fuel. Instead of ending up with a degraded, economically worthless forest of scrub hardwoods, the whole site is re-planted with conifers. Should this stand conversion practice occur on a large scale, the quality and economic value of Canadian forests will increase substantially.

While Canada has a large coastal area, exploiting aquatic biomass is not seen as economically viable even when viewed from a longer-term perspective. The energy cost of collecting this biomass is high and it could only be done during certain times of the year.

Similarly, the conversion of foodstuffs into such energy products as ethanol must be approached with considerable caution. As the American experience has shown, the subsidies for producing ethanol from agricultural biomass can be significant and may end up permanently diverting farm land from agricultural production. As well, the cost of certain foodstuffs used in energy production could increase beyond what market forces in agriculture would normally dictate.

Recommendations

Regarding bioenergy technology, it is recommended that:

1. Greater emphasis should be placed on increasing the biological productivity of energy-related biomass, through such techniques as genetic engineering and improved silvicultural practices, to reduce the future cost of bioenergy feedstock.

2. Continuing emphasis should be directed at developing enhanced machinery for biomass energy plantations, in conjunction with appropriate industrial partners.
3. Bioenergy systems used by the forest products industry should continue to be made more efficient to improve their environmental performance and reduce operating costs.
4. Market development should be encouraged for an array of products based on the cellulose, hemicellulose, and lignin derived from fractionation of forest biomass.

5 PEAT

Description of Peat Technology

Peat is an unfamiliar substance to most Canadians despite the fact that peatlands — bogs, fens, swamps, and marshes — cover an estimated 12% of the country (see Figure 34). These peatlands, and those elsewhere on the planet, were formed 10 000 to 14 000 years ago as the world's last ice age came to an end.

Peat, often described as a young coal or old biomass, can form rich organic soils. Indeed, some former peatlands, such as the Holland Marsh near Toronto, Ontario, have been drained and are today highly productive agricultural regions.

In a bog, peat is about 97% moisture and in fact contains less solids than milk. There are many varieties of peat and they are classed according to the dominant plant materials that led to their formation. For instance, Sphagnum peat, brownish in color and spongy in texture, originated largely from the Sphagnum plant. Because of the resistance of Sphagnum to decomposition, this peat is usually not highly decomposed, so the entire structure of the original plant form may be observed. Amorphous peat, however, is highly decomposed and the plant materials that constitute its blackish mass cannot be visually identified. Sedge peat, brown moss sedge peat, woody sedge peat, and feather moss peat are moderately decomposed.

On the von Post scale, which grades peat according to the degree of decomposition and, indirectly, its energy value (H 1 indicates low decomposition and H 10 high), Sphagnum peat is rated H 1–3, compared to H 6–10 for amorphous peat. Technically and economically, the best fuel peat is a highly decomposed muck-like material that registers H 5 or higher on the von Post scale.

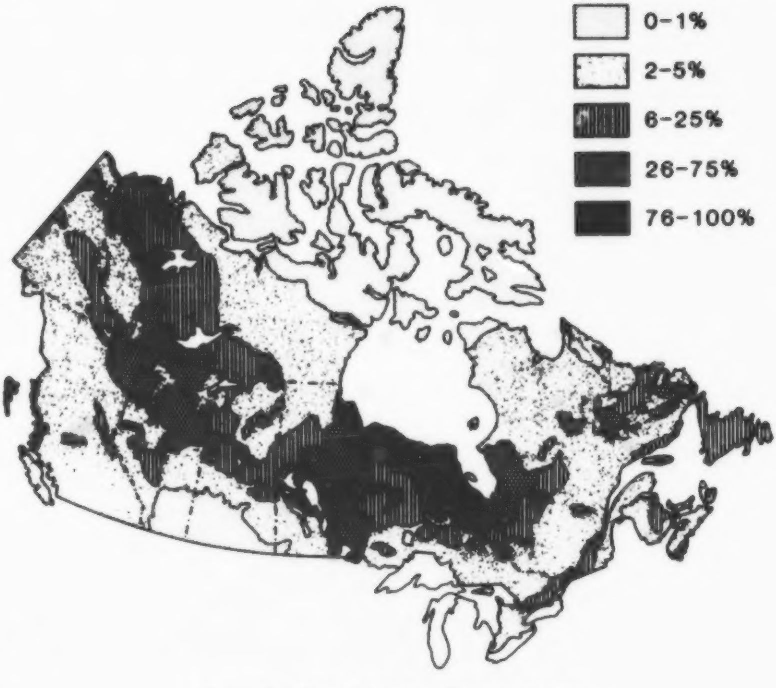


Figure 34 Distribution of peatlands in Canada

Fuel peat contains 50–60% carbon, 30–40% oxygen, 1.0–2.5% nitrogen, and 0.1–0.2% sulphur (see Table 5 for a comparison of peat with other fuels). As is the case with biomass materials, peat can be gasified and converted into methanol. Its liquid residues are fermentable.

Program Rationale and Background

Despite the vast peatlands in Canada, peat has to date never been an important fuel, largely because of its high moisture content. Oil, gas, coal, and wood have always proved more convenient or economic choices.

Indeed, only once previously in Canada's history has any government given serious attention to exploiting peat's energy potential on a wide scale and that happened in Ontario immediately following World War I. The

Table 5. Comparison of the properties of various fuels

Properties of fuels	Heavy fuel oil	Coal (bituminous)	Coal (lignite)	Peat	Wood
C, %	83–86	76–87	65–75	50–60	48–50
H, %	11.5–12.5	3.5–5.0	4.5–5.5	5.0–6.5	6.0–6.5
O, %	1.5–2.5	2.8–11.3	20–30	30–40	38–42
N, %	0.2–0.3	0.8–1.2	1–2	1.0–2.5	0.5–2.3
S, %	2.0–2.8	1–3	1–3	0.1–0.2	—
Ash content, %	0.3	4–10	6–10	2–10	0.4–0.6
Melting point of ash, °C	—	1100–1300	1100–1300	1100–1200	1350–1450
Volatiles, %	—	10–50	50–60	60–70	75–85
Bulk density, kg/m^3	920–970	720–880	650–780	300–400	320–420
Effective heat value of dry matter, kcal/kg	9900–10000	6800–7900	4800–5800	4700–5100	4400–4600
Operational moisture, %	0.1	3–8	40–60	40–60	30–55
Effective heat value at the lowest operational moisture content, kcal/kg	—	6570–7640	2640–3240	2500–3000	2900–3040
Effective heat value at the highest operational moisture content, kcal/kg	—	6200–7220	1560–1960	1780–1960	1650–1740

provincial and federal governments, worried about energy shortages in Canada's industrial heartland, sponsored a major peat demonstration project at Alfred, Ontario, near Ottawa (see Figure 35).

Despite this effort, which led to the development of some impressive harvesting technology, applied later in Europe and in Canada's horticultural peat industry, new discoveries of oil, gas, and coal rendered peat energy less economic.

Not until the oil shock of the 1970s was interest once again shown in peat energy. Its sheer quantity could not be ignored. In total, the country's peat resource — much of it found in the northern part of Canada — has an estimated energy content of 6.7×10^{21} J, marginally greater than the energy contained in oil sands, 5.8×10^{21} J. The peat resources of southern Canada are estimated to contain 2.7×10^{21} J of energy, equivalent to all of Canada's coal resources.

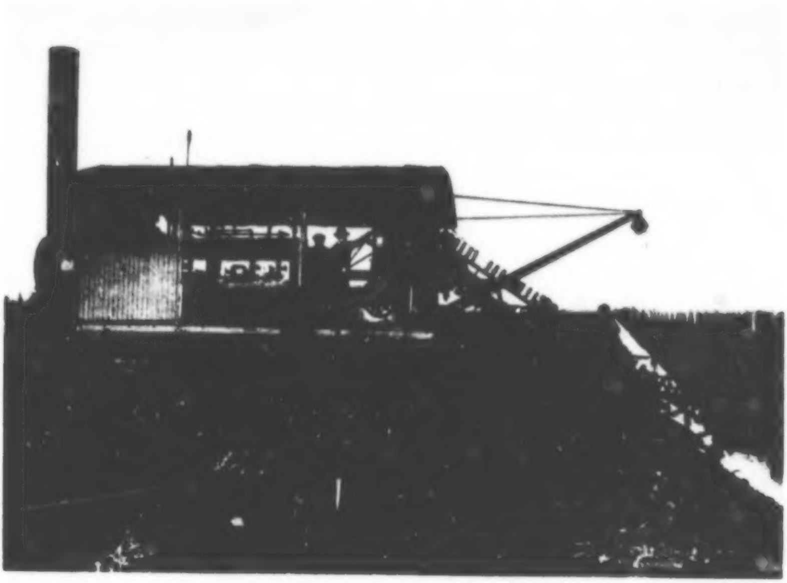


Figure 35 Peat mining at Alfred

A significant demonstration of mechanized peat mining was undertaken at Alfred, Ontario, earlier this century. Pictured is a peat mining machine probably developed for this project.

National Research Council Role in Peat Energy

The National Research Council's peat program was based on the belief that peat would be best suited as a regional energy option, particularly in Atlantic Canada where the price of imported oil was especially high. Peat could fuel small electrical generating plants and industrial boilers, especially where plants were located near peat deposits. Moreover, since dewatered peat has many similar characteristics to biomass, the latest developments in bioenergy could be applied to exploit peat's energy value.

Based on regional energy demands and the limited information available on the peat resource during the late 1970s, it was postulated that fuel peat could contribute 1% of Canadian energy needs by the end of the century. This would require the mining of 15 to 20 × 10^6 m^3 of peat every year, an activity that could involve 40 000 ha.

The National Research Council's peat program thus not only supported the development of improved mining, processing, and combustion technologies, but also placed great importance on the environmental impact of peat mining. This included monitoring the effects of peatlands mining on nearby rivers and lakes, studying the impact on wildlife, and developing peatland reclamation strategies.

The peat program also funded the development of methods that could increase the efficiency of classifying and assessing Canada's peat energy resources. Additionally, NRC's Atlantic Research Laboratory undertook to investigate the use of peat as a raw material from which chemicals and other commodities, such as coke and briquettes, could be produced.

International Status of Peat Energy Technology

Leading Countries and Performers

It is estimated that the current annual worldwide energy contribution of peat is about 1100 PJ. In the USSR, where peat is considered an important regional energy source, the installed capacity of peat-fired electrical generating plants may be as high as 10 000 MW.

In Ireland, more than 20% of the electricity is generated by peat-fired plants and, in Finland, 2.5% of that nation's energy comes from peat. Finland's goal is to triple peat's energy contribution. Finland's peat industry is highly developed, by world standards, with several companies manufacturing such products as peat sod cutters, extruders, and collectors, as well as hand-held devices that quickly determine the moisture content of peat, peat pelletizing machines, and peat coke.

The Domestic Fuel Laboratory in Finland, with an annual budget of more than $2.3 million and a staff of 64, is responsible for various aspects of peat R&D, including peat production, handling and storage, combustion, testing, standards, and related environmental matters. As part of its combustion research program, this organization developed a 15-kW combustion unit that burns peat pellets.

The power station at Tampere demonstrates the increasing technical sophistication of Finland's peat program and the payoff of research. This station has two boilers, each capable of generating 60 MW of electricity and 120 MW of heat for district heating. By devising a new method for quickly drying peat prior to its combustion, the power company was able to burn 95% peat and 5% oil in a recent conversion of an oil-fired boiler to peat. By comparison, the first boiler to be converted burns 84% peat and 16% oil.

Research Agreements and Collaboration

Canada participated in two significant international peat activities. It joined the International Peat Society (IPS) and also took part with Sweden, Finland, and Ireland in the International Energy Agency program for the use and production of peat.

The International Peat Society is a learned society consisting of individual members and national committees and its basic goal is to promote the transfer of peat technology internationally.

The IEA committee, which dealt with peat energy R&D, had four members: Canada, Sweden, Finland, and Ireland. The committee supports efforts to improve milled and sod peat production techniques, development of dewatering technology, basic research in peat dewatering, peat classification and standardization, and the exchange of scientific information.

Participating in these organizations enabled Canada to become quickly aware of the state-of-the-art in peat technology.

The Status of Peat Technology in Canada

As an energy commodity, the short- and medium-term prospects for peat are not encouraging. It is in many ways an energy source of last resort, since it must compete with wood energy, natural gas, coal, and relatively cheap oil.

On the positive side, peat contains little sulphur and heavy metals, so it is a relatively clean-burning fuel. On the other hand, peat mining affects wildlife habitats and if pursued on a large scale could have major environmental consequences unless appropriate attention is paid to environmental restoration.

In the longer term, the sheer size of the peat resource likely means Canada cannot completely ignore its energy potential. The modest peat R&D program undertaken in Canada in 1980–84 provides evidence that more efficient and environmentally acceptable ways to mine peat can be commercially developed.

Wet Mining

Today, peat is harvested through "dry mining" techniques, that is, the peat is either extruded into sods or milled, and dried by the sun to reduce moisture content to 35–50% (see Figure 36). It is then gathered and transported.

The peat program developed another alternative, "wet mining," which worked well in a test carried out in cooperation with the New York State Energy Research and Development Authority. The project involved breaking up the peat in a bog with a high-pressure stream of water, and pumping the resulting peat slurry to a dewatering area (see Figures 37–40).

Figure 36 Dry harvesting of peat

In "dry mining" peat harvesting, the peat bog is first drained and then cleared of vegetation. Machinery cuts the peat into sods, which initially contain about 90% water. Natural drying will reduce moisture content to less than 50%.

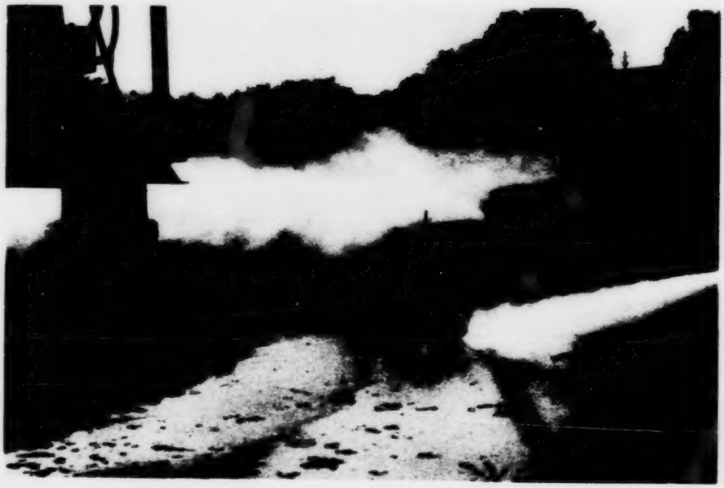


Figure 37 Wet mining of peat

In the "wet mining" of peat, water under high pressure breaks a peat bog apart.

Figure 38 Pump insertion into slurried peat

Figure 39 Slurry discharge

The peat slurry is pumped through a pipeline to a settling pond or to a dewatering plant.

The key to making this process viable was a prototype peat slurry pump/macerator designed and developed under the peat program in cooperation with Monenco and Allis–Chalmers Canada Inc. The pump, with an internal macerator that pulps and homogenizes the peat, is capable of pumping 11 000 L/min of peat slurry (containing 8% solids).

Wet mining has several important advantages over conventional peat mining methods. It is not dependent on weather and, in moderate winter climates, can be undertaken most of the year, rather than in the three or four warmest months as is currently the case in Canada's horticultural peat industry. It therefore becomes unnecessary to stockpile large quantities of peat.

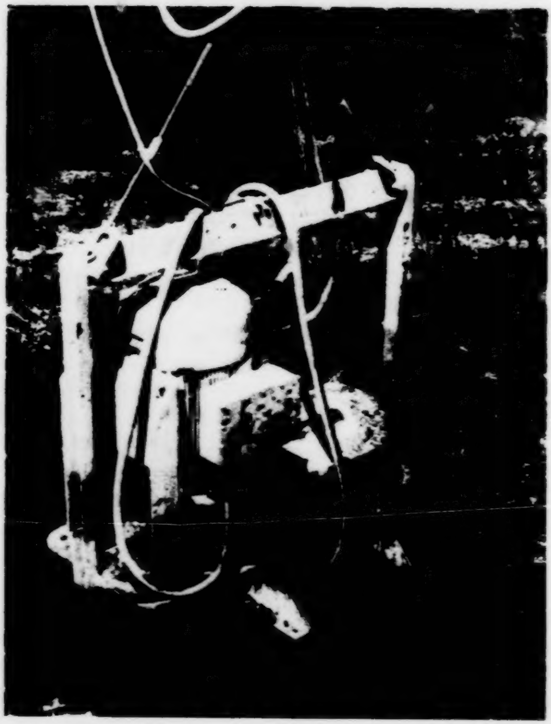


Figure 40 A close-up view of the peat slurry pump/macerator

Moreover, dry mining requires the clearing of large areas of peatland, draining them of water, and preparing the surface for production vehicles. Wet mining, by extracting the entire depth of a deposit in one pass, will affect annually about 1/50 of the area that dry mining does. Current milled peat operations use very large and extensive areas because each year only 10–15 cm of the surface layer is removed. The impact on the environment of wet mining would be less noticeable and gradual, permitting immediate reclamation of mined peatlands.

Wet mining has the added advantage of not requiring large-scale drainage operations well in advance of the actual mining step and is less likely to interfere with the nearby water systems.

Dewatering Techniques

One of the major challenges in making peat energy more economically attractive is to find efficient, yet inexpensive, means to remove water from peat, in effect to separate the fine peat particles from water molecules. The task is a difficult one because the fine peat particles are negatively charged and repel one another, but readily join water molecules.

As noted earlier, the most desirable fuel peat is a jelly-like muck whose very nature prevents easy separation of the fuel from the water molecules. However, a variety of methods can modify the electrostatic forces that hold peat and water in a stable complex. These include exposing the peat's gel structure to mechanical forces (such as maceration), thermal treatments, floculants (which encourage clumping of peat particles), and surface-active agents.

Groups at the Ontario Research Foundation, McGill University, and NRC/Université de Sherbrooke have been working on aspects of the dewatering problem. Their goal is to reduce the moisture content of the mined wet peat slurry (1 t of fuel in 15–20 t of water) to 50–70% (or 1 t of fuel in 1–2 t of water). Once this latter stage is reached, traditional drying techniques, such as pressing much of the remaining water from the peat or thermally drying it, can produce fuel peat for shipping or burning.

These groups have been successful in meeting some of their dewatering goals, although each of the methods has its own strengths and weaknesses. The final process may very well be a combination of the different options. What they have established is that macerating peat and heating it to moderate temperatures (about 150°C) aid in removing water, with little loss to the peat's fuel value.

For example, in the NRC/Université de Sherbrooke process, peat is passed through a reactor vessel where it is exposed to heat and mechanical forces; this produces an easily pressed peat retaining 85% of its initial fuel value. McGill researchers have applied floculants to heated peat to obtain large improvements in water removal. Moreover, by adding nutrients to the water pressed from wet peat, McGill researchers have also been able to produce the necessary floculating agents from bacteria and yeasts, which feed on the dissolved carbon found in this waste water. The most effective biological floculating agent was found to be protonated chitasan, a component of the cell wall of the yeast *Rhizopus arrhizus*. Similar synthetic dewatering agents were also found to be effective.

Using Microbes to Produce Chemicals from Peat

Horticultural peat, which is not highly decomposed, could, through certain technological developments, serve as a feedstock for the production of ethanol, acetone, and butanol. In a research project funded by NRC and supervised by Frank Maine Consulting Ltd., Guelph, Ontario, horticultural peat was subjected to a controlled high-pressure-steam process to release a complex mixture of sugars, which was then fermented by microbes.

Certain microorganisms, such as strains of clostridia, are able to metabolize complex mixtures of sugars to produce butanol, ethanol, and acetone by fermentation. Clostridia strains were able to grow well on the sugars extracted from the peat by the pressurized steam process. Although the quantities of butanol and ethanol produced in this project were low, researchers concluded that larger quantities of peat extract would permit greater control of the fermentation process and increase yields.

Peat Gasifier/Burner

A Wet Cell Burner developed by Lamb–Cargate Industries Ltd., which can burn wood (hog fuel) with a moisture content as high as 60%, was also tested on New Brunswick peat. The results indicated that this burner could accommodate fuel peat.

The milled fuel peat contained 46–64% moisture, with the drier fuel producing 2.75 GJ/h and the wetter fuel, 1.29 GJ/h. The peat is gasified in the lower chamber of the wet cell unit, and the resulting gas burned in the upper chamber (see Figure 41).

Probing Peatlands with Radar

Advanced electronics may assist in accurately determining the full extent of Canada's peat resource. Manual measurement techniques, which involve driving probes deep into peat deposits, are not only physically demanding but time consuming.

A survey of peatlands in eastern Newfoundland by Remotec Applications Inc. suggests that impulse radar can provide reliable estimates about the depth and volume of peat deposits in considerably less time than manual measurement techniques. In one case, an all-terrain vehicle towed 80- and 400-MHz radar systems and was able to profile peat to a level of 8.1 m, the maximum depth encountered. The ground-based profiles revealed not only distinct peat layers, but also the presence of boulders and woody remains.

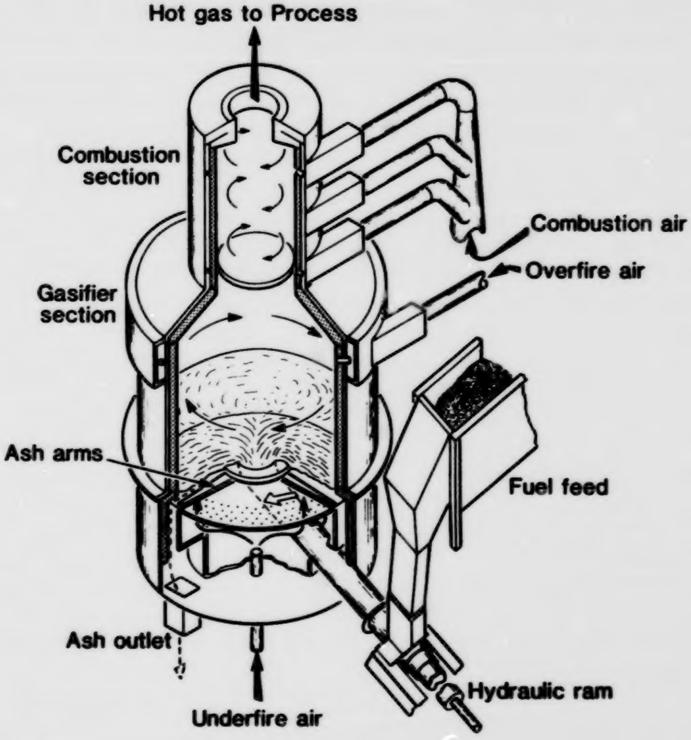

Hot gas to Process
Combustion section
Combustion air
Overfire air
Gasifier section
Ash arms
Fuel feed
Ash outlet
Hydraulic ram
Underfire air

Figure 41 Hog fuel burner

The Lamb–Cargate Wet Cell Burner is being used by the forest products industry to gasify and burn very moist wood wastes (hog fuel), but it could also be fueled by peat. This schematic shows how peat would be fed into the wet-cell unit, gasified, and finally burned.

In the second case, a helicopter towed 80- and 120-MHz radar systems. The results were poorer; even when the radar was held only 1.5 m from the surface, radar could probe no deeper than 4.8 m into the peat.

While ground-based radar surveys can provide valuable information about the quantity of peat, they do not appear to provide definitive information about the quality of peat. However, it may be possible to gain some insights into peat quality by relating the layers detected by radar to changes in the physical or chemical properties of peat.

Economic Prospects for Peat Energy

As a fuel for a small regional electrical generating plant, peat energy would be economic at an oil-equivalent price of more than $30 a barrel. There are no fundamental technical barriers impeding the exploitation of peat energy. If an energy crisis were to emerge, Canada could quickly harness its peat resources.

No significant peat energy application projects have been developed during the past decade. Fuel peat must compete against bioenergy, notably wood wastes. In many cases, wood wastes also represent an environmental problem for the forest products industry, so firms in this sector have an additional reason for favouring wood energy over peat, even if the latter was similarly priced.

Recommendations

Regarding peat energy technology, it is recommended that:

1. Modest support should be provided to Canadian laboratories to develop fuel quality standards for peat in collaboration with other nations such as Finland.
2. Wet mining should be encouraged to further peatland development and utilization, in view of the environmental and seasonal inhibitions to conventional dry mining of peat.
3. Research into peat slurry dewatering by biological and mechanical means should be continued to permit development and demonstration of a complete wet mining dewatering system.
4. Sufficient environmental research should be continued to enable the development of sound policies regarding the exploitation of Canada's peatlands.
5. The horticultural peat industry should be assisted and encouraged to exploit peat both as a fuel and chemical feedstock.

6 HEAT PUMPS

Description of Heat Pump Technology

In a natural environment, heat flows from warm areas to cooler ones until an equilibrium is attained. A heat pump is a mechanical system that, in specific applications, reverses this natural energy flow.

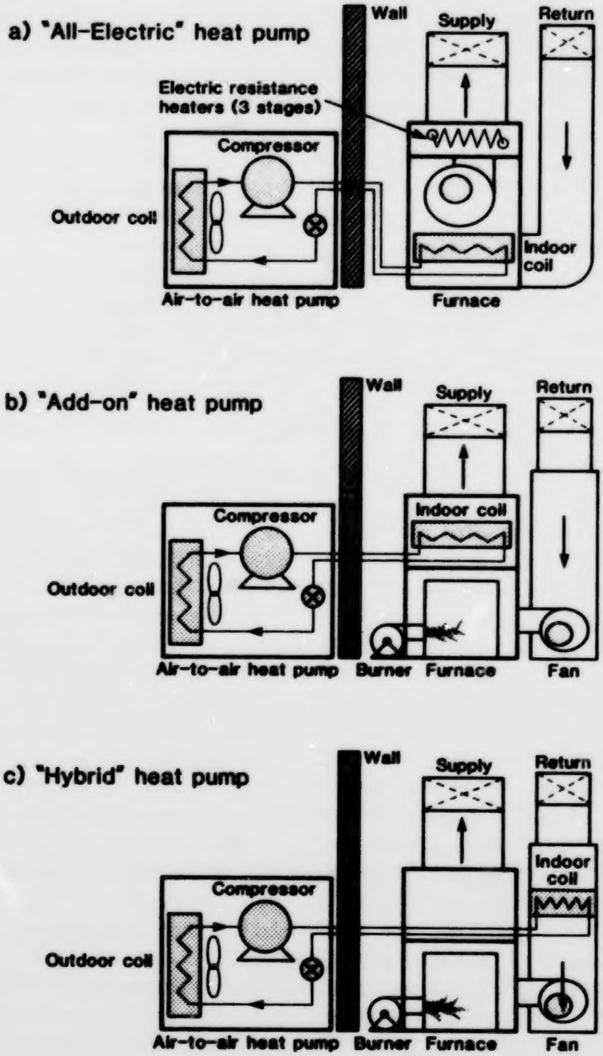
The most widely used heat pump in Canada is the refrigerator, which extracts heat from the food storage compartment and delivers it to the surrounding room. Another common appliance, the air conditioner, is also a heat pump.

From an energy conservation perspective, though, heat pumps are devices specifically designed to extract heat economically from air, water, ground, and, in industrial plants, from low-temperature sources such as waste water and steam. What makes the heat pump attractive is that it converts low-grade thermal energy into higher-grade, more useful thermal energy.

In regions of Canada where winters are not severe, reversible heat pumps — designed to heat buildings during the winter and cool them during the hot summer months — are becoming increasingly common because of their economic operation. However, the air-to-air heat pump does not operate efficiently where winter is severe, in other words, where the source energy is at a very low temperature.

The air-to-air heat pump (Figure 42) found in many Canadian residences works on a vapour compression cycle. It consists of a working fluid (or refrigerant) for transporting heat, an evaporator, compressor, and condenser.

To extract heat from the outside air, the refrigerant, which has a low boiling point, must be colder than the external environment. This cold refrigerant is piped to an external heat exchanger called an evaporator, where it begins to boil and change state from a liquid to a vapour by absorbing heat



a) "All-Electric" heat pump

b) "Add-on" heat pump

c) "Hybrid" heat pump

Wall
Supply
Return
Electric resistance heaters (3 stages)
Compressor
Outdoor coil
Indoor coil
Air-to-air heat pump
Furnace
Wall
Supply
Return
Indoor coil
Compressor
Outdoor coil
Air-to-air heat pump
Burner
Furnace
Fan
Wall
Supply
Return
Indoor coil
Compressor
Outdoor coil
Air-to-air heat pump
Burner
Furnace
Fan

Figure 42 The heating mode of three residential heat pump systems

from the surrounding air. The resulting superheated vapour then passes through a compressor and, due to compression, its temperature is further increased. The superheated vapor is then circulated to a condenser, where it is changed into a liquid, releasing the heat previously absorbed from the low-temperature source and the energy of compression.

Heat pump efficiency is expressed by the coefficient of performance (COP), the ratio of energy delivered by the heat pump to energy required to run it. For air-to-air heat pumps, operating at an outside temperature of 0 to 20°C, a seasonal COP between 1.5 and 2.0 is common.

Heat pumps vary in size from as small as 2 kW ouput to as large as 11 MW in a single unit. They are not necessarily based on the vapour compression cycle. The chemical heat pump, described later in this chapter, has no compressor and instead exploits chemical reactions.

Program Rationale and Background

Following the oil shock of 1973, NRC undertook to investigate the heat pump's potential in energy recovery. The Division of Building Research (DBR) (now designated the Institute for Research in Construction (IRC)) began by reviewing heat pump technology and its various residential applications. Researchers were especially interested in the technical and economic feasibility of using heat pumps for domestic space and water heating, as well as recovering heat from building exhaust air.

Initially, much of the emphasis centered on the air-to-air (air-source) residential heat pump, but longer-term research was also undertaken. The feasibility of extracting heat from ground or groundwater was evaluated, along with district heating schemes that employed heat pumps.

By 1979, as oil prices escalated sharply once more, industrial heat pump applications were included in the program and became a major focus of NRC activities. Many industrial sectors, notably the pulp and paper and petrochemical industries, release huge quantities of heat into the environment in the form of waste steam and warm water. Surveys by the Department of Energy, Mines and Resources determined that heat pumps could economically recapture much of this "waste" heat.

At the same time, the Division of Mechanical Engineering (DME), which had gained years of experience in refrigeration technology in its Low Temperature Laboratory, commenced a program to develop expertise in designing air-source heat pump components and systems. The goal was to provide the technical base that would enable industry to produce residential heat pumps more suited to the harsher Canadian winters.

As part of this effort, the Division of Mechanical Engineering constructed a psychrometric calorimeter, a facility that can precisely measure the performance of heat pumps. This can help evaluate new Canadian-developed products and aid in setting standards for heat pump performance.

In 1980, NRC began funding energy studies dealing with promising applications of heat pumps in a variety of industrial and commercial establishments, including restaurants, laundries, and food processing plants. As a result of these studies, the private sector implemented numerous demonstrations with the aid of funding from the National Energy Program. The National Research Council provided engineering and scientific consultation and funded the acquisition of operating data and the preparation of reports.

Consulting engineers were also contracted to investigate the potential of large chemical and steam-generating heat pumps, which were not yet commercially available but had significant potential to recover energy in the heavy process industries.

International Status of Heat Pump Technology

Leading Countries and Performers

Although heat pumps are found in virtually all industrialized nations, Japan and Sweden are the leaders in applying and developing heat pump technology.

Japanese industry has made significant improvements in residential heat pumps by developing solid state devices that allow more precise control of the compressor's operation to match the heating load. This reduces the consumption of electrical energy.

The Japanese have also reduced the size of key components of air-source heat pumps, such as the compressor and condenser. These components are available to Canadian firms manufacturing heat pumps.

Sweden leads the way in the development and application of industrial heat pumps. ASEA, one of that nation's dominant companies, manufactures an 11-MW heat pump, the world's largest. It has been connected in multiple units to provide 30 MW capacity to district heating systems. The Swedish pulp and paper industry is also using large units for heat recovery.

Part of the reason for the widespread acceptance of the heat pump by Swedish industry can be attributed to government-subsidized low interest rates, which encouraged corporations to invest in energy conservation equipment. The government also enables industry to investigate innovative methods of energy conservation by offering grants through the Oil Substitution Fund.

Research Agreements and Collaboration

Canada joined three of the major activities supported by the International Energy Agency's Heat Pump Executive. It became a member of the IEA Heat Pump Centre which conducts engineering analysis of heat pumps, maintains a heat pump database, and publishes a newsletter as well as summaries of research, development, and demonstration reports.

Another project involved the gathering of data from demonstrations of industrial heat pumps in several countries. The reports on these demonstrations contain many useful insights into the role of the heat pump in energy conservation.

Canada also undertook the lead role in an IEA project that seeks to develop more efficient heat pump technology for extracting heat from the ground. This involves research and demonstration of prototype ground-source heat pumps at NRC's campus in Ottawa, as well as in Germany, Switzerland, and the United States.

The Status of Heat Pump Technology in Canada

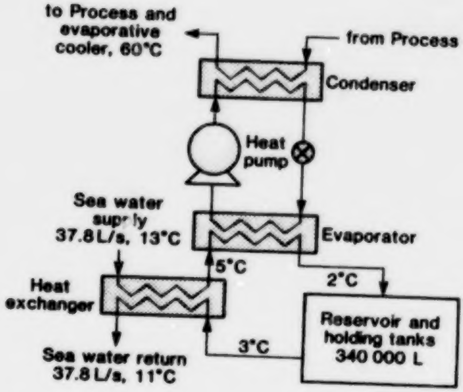
Tapping the Heat of Ocean Water

Fish processing plants or alternatively commercial office buildings can be heated by the energy extracted from ocean water.

The most successful demonstration of an industrial use of a heat pump involved Clearwater Lobster Ltd., based in Nova Scotia. This heat pump system was designed and manufactured by J.H. Lock & Sons, Dartmouth, with NRC collaboration, to cool lobster ponds. It uses the rejected heat to raise the temperature of cooking and washing water to 60°C. Lowering the temperature of the lobster ponds extends the marketing seasons, decreases cannibalism, and controls disease. The result is higher production and greater revenues.

As illustrated in Figure 43, incoming ocean water has a temperature of 5°C, which the heat exchanger and heat pump bring down to 2°C. Using the rejected heat within the plant is expected to reduce annual energy costs by $66 000.

The energy payback for this particular system is 6.3 years. Had all the rejected heat been used for process water heating, energy savings would have reached $135 000. This represents an energy payback of 3.1 years on the capital invested. However, it was also determined that installation of the heat pump increased the value of lobster production by $162 000 annually, so the actual payback to the company was 1.8 years.


to Process and evaporative cooler, 60°C
from Process
Condenser
Heat pump
Sea water supply 37.8 L/s, 13°C
Evaporator
5°C
2°C
Heat exchanger
Reservoir and holding tanks 340 000 L
3°C
Sea water return 37.8 L/s, 11°C

DATA:

Process	Supply process water
Waste heat source	Sea water
Heat pump output	614 kW
Working fluid	R-12
COP	3
Capital cost	$418 000
Energy savings	$66 000
Production savings	$162 000
Total savings	$228 000
Payback	1.8 a

Figure 43 Schematic of the heat pump system at the Clearwater Lobster plant in Nova Scotia

According to one analysis, the heat available from sea water in all Canadian fish plants could replace the equivalent of 3.5 million barrels of oil per year, or 21 PJ/a. However, the energy savings are not restricted to the fish processing industry, since many industrial and commercial complexes are near large bodies of water and could tap the heat they contain.

From a technical and operating point of view, the Clearwater Lobster project provided valuable experience in dealing with the problems of using salt water as a heat source. These included corrosion, biological fouling of heat exchange surfaces, silting, and the selection of the correct refrigerant.

Ground-source Heat Pumps

Energy can be extracted from the ground to heat buildings. Recent research programs have undertaken to improve the technical and economic efficiency of ground-source heat pumps. The Division of Building Research, NRC, and organizations in Germany, Switzerland, and the United States are demonstrating improved ground-source heat pumps as part of an IEA initiative, as noted previously.

The main challenge is to reduce the high-capital cost associated with the heat exchangers and the large earth volume required. Made of plastic or metal piping, they are placed horizontally in the ground (about 1.5 m below the surface) or, alternatively, vertically into deep holes. The holes are then filled with wet sand.

The National Research Council's latest prototype of a ground-source heat pump consists of a 2-cm-copper pipe rolled into a 15-m-long spiral that is placed in a 30-cm-wide hole (see Figure 44). A brine refrigerant, cooled to −3 to −7°C, circulates through the copper spiral and absorbs the ground heat. As winter progresses, the ground freezes to form an icy core the length of the heat exchanger. Nonetheless, the ground temperature does not dip much below 0°C, so the refrigerant continues to absorb heat. After three months of continuous operation during the winter months, NRC's demonstration found that a practical heat extraction rate of 60 W could be achieved for every metre of the copper heat exchanger. Plastic pipes, however, could obtain only 20 W per metre because of the lower heat conductivity of plastic.

It is estimated that the spiral copper heat exchanger could reduce hole drilling by two thirds, possibly decreasing the total cost of the heat pump system by 20%.

In the summer, the frozen core of ice along the heat exchanger can provide inexpensive air conditioning. Because the heat pump's compressor need not operate, it would have a COP of 18 in its air-conditioning mode. By the end of the summer, solar radiation, heat from surrounding ground, and the demands of air conditioning will, under normal conditions, have melted the ice core surrounding the heat exchanger and reheated the ground.

It is concluded that the typical house would require four 15-m-long copper spiral heat exchangers, which would draw heat from the ground as described.

Chemical Heat Pump

The chemical heat pump proposed for industrial energy recovery is a relatively new concept and as of now no commercial installations exist in

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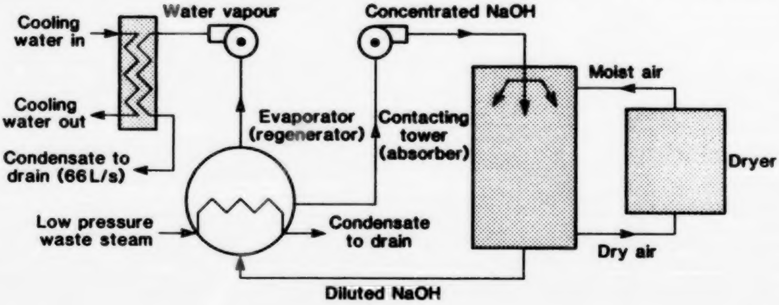
Figure 44 Ground-source heat pump

North America. However, they are technically feasible and, in certain applications, could economically recover heat from medium- and low-temperature waste heat streams, such as the warm moist air leaving paper drying equipment.

Unlike heat pumps based on the vapour compression cycle, the chemical heat pump does not use a compressor. Absorption effects replace mechanical processes to produce temperature gradients. Figure 45 shows how a sodium hydroxide chemical heat pump would extract moisture from warm moist air at 77°C (containing 15% water vapour), reduce the moisture content to 11% water vapour, and raise the temperature to 106°C.


Water vapour
Concentrated NaOH
Cooling water in
Cooling water out
Moist air
Evaporator (regenerator)
Contacting tower (absorber)
Condensate to drain (66 L/s)
Dryer
Low pressure waste steam
Condensate to drain
Dry air
Diluted NaOH

DATA:

Process	Paper drying
Waste heat source	Low pressure steam
Output	17 400 kW
COP	N/A
Capital cost	$3 000 000
Payback	2.7 a

Figure 45 Schematic of a chemical heat pump for recovering heat in a pulp and paper plant

The 77°C moist air enters the top of a contacting tower and is sprayed with a sodium hydroxide solution, containing 40% water, at 80°C. This triggers an absorption process as the air – sodium hydroxide mixture falls, in stages, through the tower. Heat and mass transfer effects occur as some of the water vapour is absorbed by the sodium hydroxide solution. The resulting heat of dilution also produces heat transfer by convection from the solution to the moist air stream. The net result is a reduction in moisture content of the air and an increase in temperature of both the air and the sodium hydroxide solution.

Once the last traces of sodium hydroxide are removed from the now hotter drier air, it is returned to the paper drying equipment. The diluted sodium hydroxide goes to an evaporator (where the excess water is evaporated) and then is fed back into the contacting tower. The water vapour is desuperheated and condensed by a water-cooled condenser.

Steam-generating Heat Pump

Vast quantities of warm water (65 to 82°C) flow through pulp and paper plants, yet much of this energy is discarded and never exploited. A steam-generating heat pump would capture a substantial amount of this heat, converting it to medium-pressure steam.

The steam-generating heat pump is based on the vapour compression cycle. At the evaporator, where the liquid refrigerant changes into a gas, heat from the waste water is absorbed. The gas is compressed and then circulates to the condenser, where heat is released as low-pressure steam (69 kPa, 90°C). Finally, a steam centrifugal compressor turns the low-pressure steam into medium-pressure steam (240 kPa) which is fed into rollers that dry newsprint.

Ottawa-based energy consultants G.A. Robb Associates estimate that a steam compression heat pump, capable of producing 4.7 MW of medium-pressure steam for a paper mill, would cost an estimated $1.3 million and have a payback period of two years at 1985 prevailing energy costs.

Other Heat Pump Developments

Chromalox Canada Inc., with NRC assistance, developed a heating/cooling air-source heat pump for the hotel and motel industry that is now being sold in Canada and the United States. These units are compact and consume less electricity than other models. The size reduction was made possible, in part, by eliminating much of the plumbing formerly required to dispose of the air-conditioning condensate. In the Chromalox heat pump, water is directed to a small fan and discharged into the environment as a fine mist.

In houses where natural ventilation rates are low, and in particular where energy efficiency has been sought through air-tight construction, air quality may become a problem and humidity levels may build up to undesirable levels. An exhaust fan may of course be operated to increase the ventilation rate, and a heat exchanger may be used between the incoming and exhaust air streams, to reduce the building heating load. A more sophisticated approach is to use a heat pump to remove energy from the exhaust air stream and to simultaneously heat the incoming air. This important application is still at the prototype stage and represents a significant commercial opportunity for the future.

Economic Prospects for Heat Pumps

The development of new heat pump technologies promises two benefits to Canada: more efficient use of energy and new industrial opportunities.

Reports submitted to NRC's Division of Energy by consulting engineers note that the development of chemical and steam-generating heat pumps could have a large impact on industrial energy consumption. It was estimated that chemical heat pumps could recover the energy equivalent of 51 PJ/a from waste heat streams in all the industries, while the steam-generating heat pump could save the equivalent of 33 PJ/a in the newsprint industry alone.

Government-funded R&D has demonstrated that heat can be economically removed from ocean water to heat commercial and industrial buildings near coastlines. This has obvious implications for the Atlantic provinces, which are still heavily dependent on imported oil, as well as urban centers near large bodies of fresh water.

The National Research Council's demonstration of an improved ground-source heat pump, which promises to be cheaper than those that now extract ground heat, could find use on farms and other regions of the country where energy options are limited. This energy technology would create local employment because each pump is, in effect, constructed on site.

The availability of relatively cheap natural gas and other fuels has served to slow the spread of heat pumps in both the residential and commercial markets. As reported in *A Review of the Heat Pump Research and Development Program*, nearly 20000 split system air-source heat pumps (consisting of two or more component packages) were sold in 1984, compared to 250 in 1975. Sales dropped to about 12000 units in 1985 (see Figure 46).

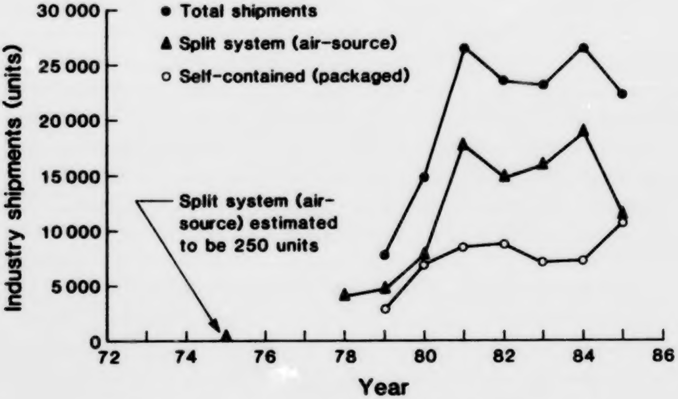


Figure 46 Heat pump shipments in Canada, all product classes

Self-contained heat pumps experienced greater sales in 1985, after a period of little growth in 1980–84. About 11 000 of these units were sold in 1985, with packaged units for office buildings, luxury apartments, and condominiums accounting for 80% of sales.

It is estimated that only 15 industrial heat pumps were sold in 1985. However, the heat pump remains economically viable in a number of industrial applications. Where a COP of 6 or 7 is indicated, the industrial heat pump can be identified as an economic proposition since a typical payback time would be less than two years.

Moreover, as the case of Clearwater Lobster demonstrates, implementing a heat pump system to serve both heating and cooling applications can make a great economic contribution. Such a system combines the delivery of heat in one location (to raise the temperature of industrial process water, for instance) with the extraction of heat in another (to decrease, say, spoilage of raw material).

A significant economic benefit to the utility industry is possible if the residential (and small commercial) heat pump could be used as a future planning element in electrical load distribution and control.

Recommendations

Regarding heat pump technology, it is recommended that:

1. Special attention should be given, respecting mid-term commercialization of residential heat pumps, to ground-source technology and to ventilation air heat recovery.
2. Research emphasis in industrial heat pumps should be placed on refrigerant technology, heat exchange surface technology, and modulation and control systems.
3. Demonstration programs should be undertaken to encourage the further development of industrial heat pump systems by Canadian companies, notably chemical and steam-generation heat pumps.
4. Utilities should be encouraged to study the residential (and small commercial) heat pump as an active element in electrical load distribution and control.

7 HYDROGEN AND ENERGY STORAGE SYSTEMS

Description of Hydrogen and Energy Storage Technology

In the late 1970s, Canada, like many other industrialized nations, began to consider the energy role of hydrogen (H_2), the lightest and most plentiful element in the universe.

On Earth, hydrogen is almost always combined with other elements (natural gas, coal, oil) but, of course, it is most abundant in water (H_2O). Since energy must be used to break hydrogen loose from these elements, pure hydrogen in its gaseous or liquid states constitutes an energy carrier or currency rather than a source of energy.

As an energy carrier, hydrogen is attractive for a number of reasons. Besides having the highest energy density per unit weight of any chemical fuel, it is also clean burning. Moreover, unlike other fuels, hydrogen can be produced by using electricity to separate water into its component parts. The electricity can be supplied by a variety of sources: hydroelectric stations, photovoltaic cells, wind turbines, tidal power facilities, nuclear power plants, and high-temperature heat sources (see Figure 47).

Many energy storage systems, including batteries and fuel cells, fall within the field of electrochemistry — the study of processes involved in converting chemical energy into electrical energy and vice versa. Since batteries, fuel cells, and water electrolysers (which split water into hydrogen and oxygen) all contain electrodes, developing more efficient electrodes can have important ramifications in all three technologies.

Program Rationale and Background

In the industrialized world of the 1970s, the prospect of more expensive oil and the eventual depletion of oil reserves prompted discussion of the

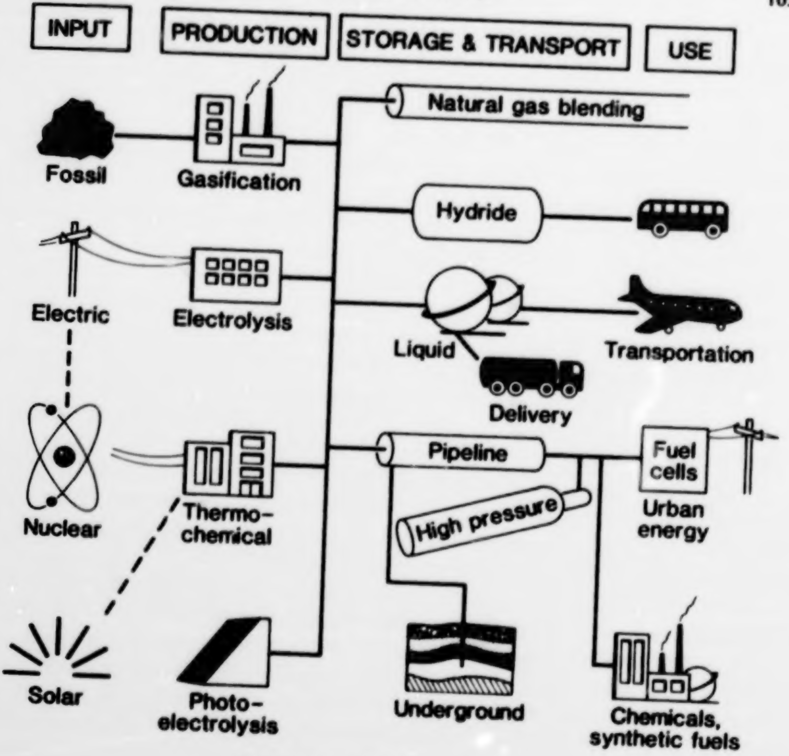

INPUT
PRODUCTION
STORAGE & TRANSPORT
USE
Fossil
Gasification
Natural gas blending
Hydride
Electric
Electrolysis
Liquid
Transportation
Delivery
Nuclear
Thermo-chemical
Pipeline
Fuel cells
Urban energy
High pressure
Solar
Photo-electrolysis
Underground
Chemicals, synthetic fuels

Figure 47 The hydrogen economy

Hydrogen can be generated from any energy source, stored and transmitted using available technology, and finally used in a vast range of applications, essentially displacing the current fossil hydrocarbon fuels. This state of affairs is referred to as the Hydrogen Economy.

hydrogen age. Many nations saw the role of electrical energy growing in importance, but also realized the limitations of electrical energy in the transportation sector. One way of dealing with the problem is to convert electricity into hydrogen fuel. Hydrogen, in effect, provides a means of storing and transporting electricity and could allow electricity to replace oil as a vehicular fuel. But, more than that, electrolytic hydrogen could also displace natural gas as a source of hydrogen for producing chemicals and upgrading crude oil.

During the late 1970s and early 1980s, the oil substitution potential of electrolytic hydrogen was considered by some federal government scientists and energy policy makers to be particularly significant, since electricity was expected to supply a greater share of energy. According to a 1978 Department of Energy, Mines and Resources view of Canada's energy future, electricity, which supplied 35% of total primary energy in 1975, could increase its contribution to 45% in 2000 and 47% by 2025.

The Canadian oil industry was cited as one large potential user of electrolytic hydrogen. The process of upgrading crude oil, oil sands bitumen, and heavy oil requires chemically combining hydrogen to increase the ratio of hydrogen to carbon. The industry currently obtains the hydrogen by reacting steam with natural gas, a process that releases hydrogen while combining the carbon with oxygen to produce carbon dioxide. More than 1.6% of Canada's total energy supply is consumed in producing hydrogen in this manner, mostly within petrochemical plants. Only about 1% of the hydrogen in Canada is at present produced by electrolysis of water.

Two notable reports in 1981 concluded that hydrogen had an important role to play in the country's energy, economic, and environmental future. In its report *Energy Alternatives* the Special Parliamentary Committee on Alternative Energy and Oil Substitution recommended that the federal government spend $1 billion over a five-year period to foster the broad development of a hydrogen-based energy system and to establish Canada as a world leader in hydrogen technologies.

Later that same year, the Ontario Hydrogen Energy Task Force released its report, *Hydrogen: A Challenging Opportunity*. The Task Force, concluding that electrolytic hydrogen could play an important role as a feedstock and fuel in the province by the 1990s, recommended the creation of an Ontario Hydrogen Development Agency. It further recommended that the agency's annual RD&D funding should, in its fourth year of operation, total at least $10 million.

National Research Council Role in Hydrogen Energy Technology

The federal government's Hydrogen and Energy Storage research program, managed by NRC, had three major long-term goals: developing advanced water electrolysers, assessing and developing techniques that would lead to greater use of hydrogen as a fuel, and identifying and developing the most appropriate energy storage technologies.

International Status of Hydrogen Energy and Energy Storage Technology

Leading Countries and Performers

The leading nations in hydrogen technology are the United States, Japan, West Germany, and France. (Canada has long been a world leader in the traditional electrolytic hydrogen and oxygen markets.) The American strength in hydrogen systems is due to that country's space program and the fact that many of its rockets and space vehicles (including the space shuttle) are fueled by liquid hydrogen. Although the United States funded a wide range of hydrogen R&D during the past decade, much of it on advanced concepts (such as the biological production of hydrogen), little of this research has to date been commercially exploited.

France, a large oil importer, saw electrolytic hydrogen produced by nuclear reactors as an important source of fuel for the future. France did not officially participate in the International Energy Agency's hydrogen program, but committed significant sums of money toward developing large-scale hydrogen production equipment, transmission lines, and storage facilities.

West Germany, with its strong petrochemical industry, has always played a major role in hydrogen-related-systems technology. The German space agency, in particular, continues to be a world leader in the production and handling of liquid hydrogen. Among its recent developments is a prototype on-board liquid hydrogen storage tank for cars and buses.

Japan's substantial R&D investment in hydrogen has covered a variety of activities. One notable achievement is the development of a high-performance auto engine that uses liquid hydrogen as a fuel.

Research Agreements and Collaboration

In 1986, Canada participated in three of the International Energy Agency's hydrogen program tasks. The first, electrolytic production of hydrogen, involves a multinational effort to drive down costs of key components of electrolysers and improve their energy efficiency. Another program, more experimental and basic in nature, is investigating photocatalytic decomposition of water — directed toward the use of sunlight to split water into hydrogen and oxygen. The third program deals with hydrogen storage, energy conversion, and safety. This covers such activities as storing hydrogen in metal hydrides and other forms, assessing heat engines and fuel cells for both stationary and mobile applications, and combatting hydrogen-induced metal embrittlement.

The National Research Council chaired the IEA Hydrogen Executive Committee from 1982 to 1984, and thereby made considerable input to the development of the international program.

The Status of Hydrogen Energy and Energy Storage Technology in Canada

Electrolysers

A main goal of hydrogen R&D around the world is to improve the performance of water electrolysers. According to an IEA prediction, the cumulative world market for water electrolysers could reach $10 billion by the end of the century and $47 billion by 2025.

One of the world's leading producers of advanced large-scale water electrolysers is Electrolyser Inc., a joint venture between Noranda Mines Ltd., The Electrolyser Corp. Ltd., and Hydro-Québec. In the world of hydrogen, the Toronto-based Electrolyser Corp. is well known for its compact electrolytic hydrogen plants. The firm has exported its products to more than 80 countries.

A water electrolyser contains many cells, each consisting of a series of negative (cathode) and positive (anode) electrodes. If the cathode and anode are on opposite sides of the same plate, then the structure is referred to as a "bipolar" design; a "unipolar" electrolyser has separate anode and cathode plates.

The electrodes, kept apart by a semi-permeable membrane or separator, are immersed in an electrolyte solution. When a current is passed through the cell, electrochemical reactions occur at the interface between the electrode surface and the electrolyte — typically water containing 25% potassium hydroxide. Hydrogen gas is produced on the cathode and oxygen gas on the anode. The separator prevents the two gases from mixing and reacting.

With funding from NRC's hydrogen program, Electrolyser Inc. was able to improve significantly the efficiency of its water electrolyser. A 100 000-A current flows through the firm's advanced EI-250 unipolar cell, containing 51 electrode plates. This cell converts 81% of the electrical energy into hydrogen (see Figure 48), compared with 70% energy efficiency for Electrolyser's older unipolar technology.

Improving the efficiency of electrolytic cells involves reducing the voltage a cell needs to decompose water into hydrogen and oxygen. Voltage losses are

Figure 48 El-250 unipolar electrolysis cells

due to several factors, such as internal cell resistance and overvoltages — voltages in excess of those theoretically required for the electrode reactions that produce the hydrogen and oxygen gases. To reduce overvoltages, Electrolyser successfully developed more efficient electrocatalysts for both the anode and the cathode. These electrocatalysts decreased the amount of energy needed to support the required electrochemical reactions.

Further, by improving the design of the cell current pathways in both the metal parts and in the electrolyte solution, Electrolyser was able to cut resistive losses substantially. Decreasing the cell voltage by these means has a direct economic payoff since less electricity is being used to produce a unit of hydrogen. Operating costs are therefore reduced.

By improving the electrodes, Electrolyser was also able to increase the current density passing through the cells and thus decrease the capital cost and the physical size of the plant. The higher the current per unit surface area, the greater the amount of hydrogen produced by a given size of electrode.

HydrogenAL, a company owned by Hydro-Québec and Air Liquide, is building a 6-MW electrolytic hydrogen plant at Becancour using Electrolyser's technology. This unit is designed to produce 3 t/d of liquid hydrogen while another 7 t will be produced from hydrogen gas supplied by a nearby chlor-alkali plant as a by-product.

Combined Electrolysis and Catalytic Exchange Process

During the course of its normal operation, an electrolyser concentrates deuterium, or heavy water, which serves the vital function of slowing neutrons in a CANDU reactor so that they can split uranium atoms. Electrolyser and Atomic Energy of Canada Limited undertook a joint R&D project to develop the combined electrolysis and catalytic exchange (CECE) process, which is based on water/hydrogen exchange. Heavy water by-product recovery from electrolysers is attractive for a CANDU system as it offers the promise of producing heavy water at a considerably lower cost than competing techniques. It is estimated that a 100-MW electrolyser plant could produce 14 t/a of reactor grade heavy water by the combined electrolysis and catalytic exchange process.

Separators

The National Research Council's hydrogen program also supported research aimed at developing thin plastic separators and solid polymer electrolyte membranes for advanced water electrolysers and other electrochemical applications. Plastic separators have the potential to operate at higher temperatures and would, therefore, increase electrical efficiency, since a higher operating temperature results in the lowering of the required cell voltage by 5 mV/C. Separators are now usually made of asbestos cloth and while they are extremely reliable they fail in strong caustic solutions above 90°C.

Research done by Daychem Labs Inc., McGill University, and the University of Calgary produced commercially promising separator technology. Daychem developed the separator's synthetic polymer (aromatic ionomer) materials and, in addition, explored cheaper methods for producing them. McGill then used these polymers to fabricate test samples of separators and also evaluated their mechanical properties. The University of Calgary tested the McGill membranes for water sorption, electrical conductance, and ion transport properties. Ballard Technologies in British Columbia, in cooperation with Daychem Labs, is further developing and testing these materials for use as separators in water electrolysers and as solid polymer electrolytes for an advanced fuel cell.

Ceramic Electrolytes

Researchers at Queen's University and McMaster University are developing ceramic electrolytes capable of conducting hydrogen ions. Such ceramic electrolytes could be used in advanced fuel cells and water vapour electrolysers of the future. The increased electrical efficiency that results from the ceramic electrolytes's ability to function at high temperatures is one of its main advantages over liquid electrolytes.

Ceramic electrolytes are based on a "two-phase" design that allows for the possibility of using the same cells in either the fuel cell mode or electrolysis mode. In addition, the ability of ceramic electrolytes to work at high temperatures, 300 to 1000°C, eliminates the need for coating electrodes with expensive electrocatalysts.

The research challenge remains to develop good ion-conducting ceramic materials with appropriate mechanical strength, tests to determine whether these materials will resist cracking under operating conditions, and cost-efficient ways to manufacture them.

Advanced Batteries

Compared to the common lead–acid battery found in cars, advanced batteries now being developed will store much more energy, an improvement required for traction applications. While the best lead–acid battery has an energy density of 40 Wh/kg, some prototype batteries now under development have achieved >100 Wh/kg.

All batteries work on the same principle, that is, electrodes of two different materials exchange ions through a liquid, solid, or gel-like electrolyte. The movement of ions through the electrolyte results in an excess of electrons at the negative electrode. If a battery is connected to a circuit, the excess electrons flow through the circuit thereby producing an electric current.

The National Research Council funded early research into the lithium – iron sulfide (Li/FeS) battery at Hydro-Québec's research institute, IREQ. This battery operates at high temperature (450°C) and is rechargeable. Subsequently, this technology was transferred to The Electrofuel Manufacturing Co., Toronto, which has developed prototype cells about the size of a paperback book and weighing 1.6 kg. Their energy density is 110 Wh/kg (see Figure 49).

The battery cell consists of a negative electrode made of a lithium/aluminum alloy, a positive electrode made of iron sulfide, and a molten salt electrolyte. When the cell is discharging electrical power, lithium ions are continually moving through the molten salt. A boron nitride separator keeps

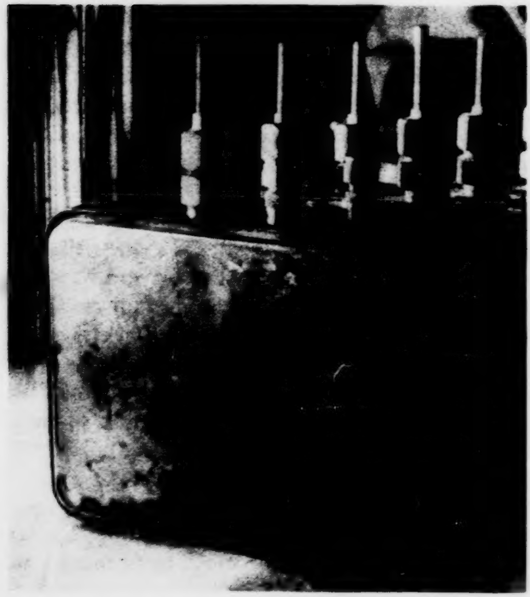


Figure 49 Advanced battery cells

This stack of lithium aluminum/iron sulphide battery cells was developed by Electrofuel Manufacturing Co. Each cell has a nominal capacity of 200 W.

the negative and positive electrodes apart. When the lithium ions reach the iron sulfide electrode, a chemical reaction occurs that converts the iron sulfide into lithium sulfide and iron. The ion flow causes the electrode to become positively charged, and the reaction provides energy.

When all the lithium has left the negative anode, leaving only aluminum, the cell is fully discharged. Recharging the cell with electricity reverses the reaction and drives the lithium ions back to the aluminum anode.

Currently, Electrofuel is designing the optimum manner of connecting the cells to produce a prototype 12-V battery, as well as the battery's thermal management system. The battery produces heat when discharging or recharging and a properly designed thermally insulating enclosure must keep an inactive battery at operating temperature for several days.

According to Electrofuel, 180 cells could power a van and 90 cells a small car. The company is looking to exploit a number of markets, including one with large potential in Canada, the mining industry. The energy density of lithium sulfide batteries is such that they could power heavy equipment. This would eliminate the exhaust fumes of diesel-powered equipment and reduce the requirement for fresh air ventilation shafts. It is the internal combustion engines of these machines, and not people, which consume the most oxygen underground.

The basic concept of the Li/FeS battery is not new — in fact, American patents on it have long since expired — but it appeared that its commercial potential was largely held back by the high price of the boron nitride felt separators. One of their functions is to prevent the buildup of long pointed crystals between the positive and negative electrodes, since these crystals cause short circuits.

Blue Mountain Pottery Ltd. subcontracted the Ontario Research Foundation to develop a prototype manufacturing technique to reduce the cost of the boron nitride felt sheets several-fold. This technique involves melting boron oxide powder, drawing it into very thin fibres, and then turning the fibres into a felt (see Figure 50). The felt is heated in a furnace in the presence of nitrogen and the oxide is burned off. After more boron oxide has been added to glue the fibres, the reinforced felt is re-nitrited once again. Oxide would melt in the electrolyte and cause the felt to fall apart.

Electrofuel, which redesigned ORF's process, now has a pilot plant producing boron nitride separators and expects that their cost will continue to drop significantly. It is anticipating significant foreign sales for this product.

Two other Canadian firms are also keen to capture part of the multi-billion dollar worldwide annual market for batteries. Moli Energy Ltd. of Vancouver is building a $40 million plant that will produce AA size lithium – molybdenum disulfide batteries for consumer electronics products. The rechargeable batteries operating at ambient temperature have double the energy density of nickel–cadmium batteries. The company is also developing "beer can" size batteries for use in vehicles and other applications. In the lithium – molybdenum disulfide battery, ions leaving the anode during the discharge phase pass through the electrolyte to a cathode made of molydenum disulfide powder. During the recharge phase, the lithium ions travel back to the anode.

Meanwhile, Powerplex, a joint venture between Magna International Inc. and Brown-Boveri, is making a major effort on the high-temperature sodium–sulfur battery. The battery is different from most others in that it has liquid electrodes and a solid ceramic electrolyte. Powerplex is now fitting prototype sodium–sulfur batteries into vans.

Figure 50 A scanning electron microscope photograph of a boron nitride felt which is used as a battery separator

Aluminum/Air Fuel Cell

Alcan International Ltd. is evaluating the aluminum/air fuel cell originally developed at the Lawrence Livermore Laboratories in Livermore, California. The fuel cell consists of aluminum anodes, a sodium hydroxide electrolyte, and an oxygen cathode supplied from atmospheric air.

Aluminum dissolves in the electrolyte and is transported to the cathode where it reacts with atmospheric oxygen. This creates a negative charge on the aluminum plate and a positive charge on the air cathode (actually made of a porous composite material). A flow of electricity results.

During this electrochemical process, the aluminum plate slowly dissolves. In an electric vehicle, water must be added to the fuel cell after 400 km and aluminum wastes removed from the electrolyte (the aluminum electrodes would be replaced at longer intervals). It is estimated that 140 kg of aluminum plates can provide enough fuel to allow an automobile to travel several thousand kilometres. Alcan's research is aimed at preventing the aluminum plates of the aluminum/air fuel cell from dissolving when power is not being withdrawn. The company has developed new alloys that significantly reduce this corrosion phenomenon.

Heat Storage Furnace

In countries where time-of-day electric rates are applied, heat storage furnaces are common. During periods when electric demands and rates are lower, the electric elements of such furnaces heat up rocks or bricks. The stored heat is released when the electricity rates are priced at their highest, at times of maximum industrial demand.

Chromalox Canada Inc., with help from the Ontario Research Foundation and funding from NRC, designed an advanced heat storage furnace. The Ontario Research Foundation developed techniques to manufacture bricks from iron oxide which can absorb considerably more heat than rock or competitive products. The iron oxide bricks, named Chromalite, can be heated to 700°C.

Prototype furnaces made by Chromalox were equipped with sophisticated temperature control devices. They can be programmed with outdoor temperature forecasts to determine the furnace's optimum storage temperature and thus prevent the storage of more heat than is required.

Several furnaces have been successfully demonstrated in the northern United States, where time-of-day electric rates are in force, and in Ontario, where they are not. The product is deemed to have significant export potential (see Figure 51).

Energy Storage Rotors (Flywheels)

Energy from engines, wind turbines, and the momentum of a vehicle can be stored in a flywheel, a mechanical device that stores energy in a rotating mass. Advanced flywheels have a large energy storage capacity: a 35-kg flywheel designed by the University of Ottawa, for instance, rotates at 22 000 rpm and stores 1.3 kWh of energy — the kinetic energy equivalent of ten 1350-kg automobiles travelling 100 km/h.

While flywheels are not now in widespread use, they have great potential as "load-levelling" devices. They can be charged when energy demand is low and then discharge the accumulated energy during peak demands. A case in point would be a bus that requires extra power for climbing a hill or for accelerating in traffic. To meet this peak demand, the bus could draw on the energy stored in the flywheel.

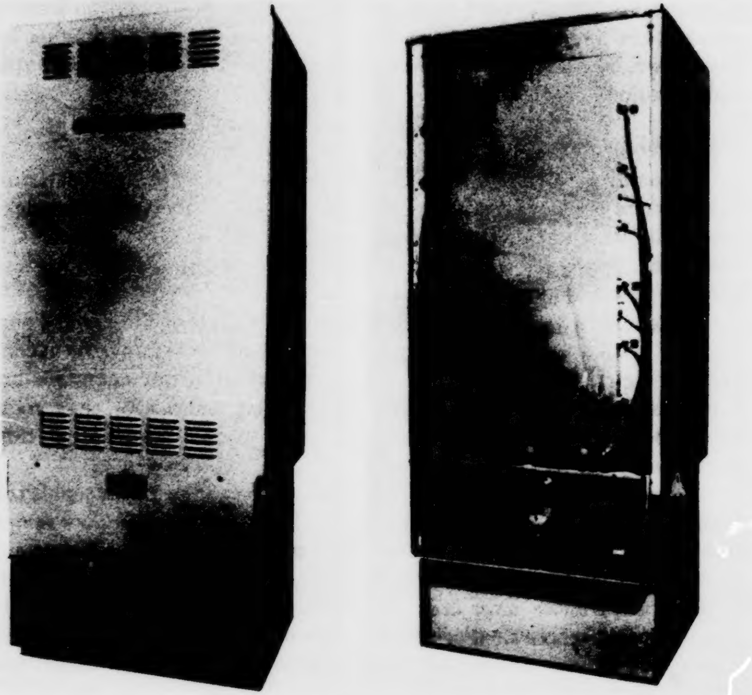


Figure 51 Front and back of a prototype heat storage furnace developed by Chromalox Canada

In theory, a full-sized city bus would only need a 15-kW engine if it had a flywheel. The reason buses actually are equipped with engines several times more powerful is to be able to meet the relatively brief peak demands.

The University of Ottawa has become a significant centre of flywheel expertise. As such, it has not only tested dozens of energy storage rotors but also developed techniques for their production. University researchers have produced four prototype flywheels utilizing such advanced fibre materials as carbon, Kevlar, and specialized glasses.

The lower speed rotor, with a design speed of 19 000 rpm, stores 1 kWh, while the higher speed rotor, 25 000 rpm, stores 1.5 kWh. Should these flywheels fail when rotating, they would merely shred and pose no threat of injury. If a high-speed metal flywheel fails, the flying metal fragments can be extremely dangerous.

The energy storage rotors built by the University of Ottawa are designed to be recharged up to 100 000 times and would have a 20-year life in a bus operating 16 h/d. These composite rotors are also designed to function in temperatures ranging from −40 to 100°C. Some of the rotors, such as the FW3 model (see Figure 52), have an open hub concept and, according to university researchers, are easy to assemble and lend themselves to mass production.

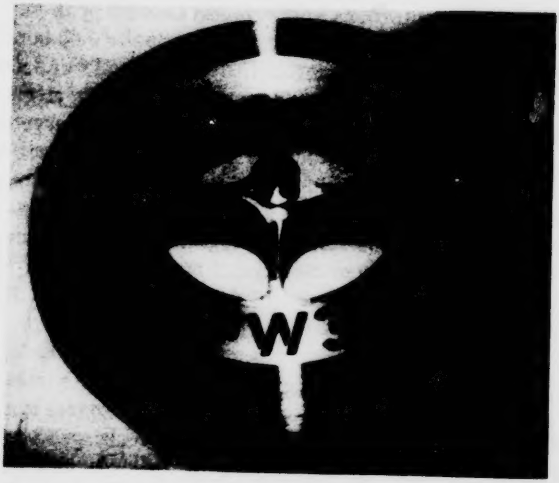


Figure 52 Energy storage rotor (flywheel) developed and produced by the University of Ottawa, Ottawa, Ontario

Liquid Hydrogen Carriers

Ammonia and methanol are called liquid hydrogen carriers because they are liquids that contain large amounts of hydrogen. The carrier can be burnt directly in an internal combustion engine or, alternatively, the hydrogen can be dissociated (separated) from the other elements and fed into an engine in its pure gaseous form. As vehicle fuels, liquid hydrogen carriers have two advantages over pure hydrogen in its gaseous or liquid states, namely, safer handling and easier storage. The challenge is to modify engines to enable them to burn liquid hydrogen carriers with the greatest efficiency.

In one project, the Manitoba Research Council (MRC) examined the combustion efficiency of ammonia (NH_3) in a modified diesel engine. Ammonia is the only common non-carbon fuel that can be conveniently stored as a liquid at room temperature. It has occasionally been used as a vehicle fuel and, during the 1940s, powered Belgian transit buses.

The Manitoba Research Council conducted its tests on a single cylinder of a multi-cylinder modern diesel engine configured to burn ammonia fuel cleanly and efficiently. The results were favourable. The engine started easily and the power output was equal to that produced with propane fuel. The engine's thermal efficiency was greater with ammonia than with diesel fuel. Unburnt ammonia concentrations were low, less than 15 ppm.

The National Research Council had also planned to collaborate with the United States Solar Energy Research Institute (SERI) and Ontario Research Foundation to gather further data on the advantages of dissociated methanol as a hydrogen carrier. Canada could produce large amounts of methanol from natural gas and wood for use as a vehicle fuel, if the need arose. Methanol dissociation produces hydrogen and carbon monoxide and has considerable attraction as a fuel and potential advantages over direct combustion of methanol. This research program, aimed at providing additional technical understanding of dissociated methanol systems, was defined but not acted on due to the termination of the energy program.

Fuel Cell Demonstration

Fuel cells convert chemical energy in hydrogen directly into electricity. Potentially more efficient than engines in converting fuels into electricity, fuel cells function much like batteries except they are recharged with fresh fuel rather than electricity. The National Research Council purchased a 40-kW mobile fuel cell power plant which was operated by B.C. Hydro to gather information on fuel cell performance and to provide an assessment of fuel cell benefits and limitations to potential users. This particular fuel cell was bought from United Technologies and is one of 49 being evaluated in the United States, Japan, Mexico, and Canada. Those evaluating the fuel cells are sharing the results of their applications.

Electrolyser Test Centre

The Noranda Research Centre in Pointe Claire, Quebec, was designated as the IEA centre for testing new electrolyser separators and various new electrocatalysts. This provided Canada with an up-to-date view of some of the important technical developments affecting this hydrogen production technology. The Department of Energy, Mines and Resources is continuing to fund the Centre as a Canadian contribution to the IEA Hydrogen agreement.

Economic Prospects for Electrolytic Hydrogen

The economic prospects for large-scale production of electrolytic hydrogen are generally dependent on two factors: the cost of electricity and the cost of oil and natural gas.

In certain regions of Canada, notably Quebec and Ontario, where large electrical generation capacity exists, electrolytic hydrogen will be an important option — possibly before the end of the century if the costs of oil and gas increase sharply. Ontario's 1981 Hydrogen Task Force report, for example, forecast that electrolytic hydrogen could be cheaper by the mid-1990s than hydrogen extracted from natural gas. However, this forecast was based on the premise that electricity would be cheaper (in 1980$) in the year 2000 than in 1980 due to an expansion of nuclear generating capacity.

According to the report's projections, electricity would cost $14/MWh in 2000, compared to $17.8/MWh in 1980. Combined with improved electrolysis facilities, the plant gate cost of electrolytic hydrogen was projected to decrease from $8.2/GJ in 1980 to between $5.6/GJ and $6.6/GJ in 2000. By comparison, hydrogen produced from steam–methane reforming was expected to increase during the same time period from $5.2/GJ to more than $10.7/GJ.

The earliest large-scale application for electrolytic hydrogen was seen to be the displacement of hydrogen in refinery product upgrading. By the year 2000, Ontario refineries could consume 30 PJ/a of electrolytic hydrogen and could find it economical to replace steam methane reformers with electrolyzer plants.

Should the price of oil and gas increase substantially, electrolytic hydrogen could also find a useful economic application in upgrading the synthesis gas produced by wood gasification and intended for the production of methanol. The status of wood gasification is described in a previous chapter dealing with bioenergy.

Finally, some lesser developed nations of the world have hydroelectric potential, but no hydrocarbon resources. Canadian firms could find a significant market in these nations for electrolysers and other hydrogen-related systems. The cost of these projects, however, is site specific.

Recommendations

Regarding hydrogen and energy storage technologies, it is recommended that:

1. Canada's leadership in electrolytic production of hydrogen should be maintained and, in particular, the Noranda Research Centre's role in testing electrolysers, separators, and related components should be supported.
2. One or more centres of electrochemical expertise should be identified in Canada to ensure availability of the fundamental science underlying hydrogen production technology and energy storage systems.
3. Sufficient applied work should be continued in batteries and fuel cells to ensure that government policy decisions are based on sound technical information, in view of the very large industrial opportunities implied.

8 FUSION ENERGY

Description of Fusion Technology

Perhaps the greatest scientific and technical challenge the human race has so far undertaken is the attempt to harness and control the power of nuclear fusion, the process that enables stars, including our sun, to produce light and heat.

In the sun's core, the strong forces of gravity and a temperature of 17×10^6 °C create conditions in which hydrogen atoms, ordinarily held apart by repulsion, collide and fuse. In fusion reactions, two hydrogen atoms are converted into a heavier helium atom (weighing slightly less than the hydrogenic atoms which formed it), plus energy in the form of light and heat.

Full-scale nuclear fusion reactors would require very small amounts of fuel. Measured by weight of fuel, the fusion process would produce about one million times the energy of fossil fuels.

However, man-made fusion reactors would initially be fueled with the more expensive isotopes of hydrogen, deuterium and tritium, because this combination of hydrogen burns at much lower temperatures, relatively speaking (see Table 6). A litre of ordinary sea water contains enough deuterium to produce the energy equivalent of 182 L of gasoline.

Replicating the heavy gravity of the sun's core is impossible on earth, so fusing regular hydrogen atoms in a machine is simply not being considered. Fusing the nuclei of deuterium and tritium is practically feasible, but requires extremely high temperatures, in the order of 100×10^6 °C (several times the temperature of the sun's interior). This high temperature, essential for fusion reactions to occur in reactors, causes some of the nuclei to move with such speed that they overcome the positive electrostatic repulsive charges ordinarily keeping them apart. The nuclei collide and fuse, producing helium and neutrons.

Table 6. The ignition temperatures of various hydrogen isotopes

Fusion Reaction	Energy of Reactants J/g (×10^{10})	Ignition Temperature °C (×10^{6})
D + T → ^{4}He + n	16.9	77
D + D → ^{3}He + n	4.0	773
D + D → T + p	4.8	386
D + ^{3}He → ^{4}He + p	17.7	620
D + ^{10}B → 3^{4}He	3.2	2300

Although deuterium and tritium are chemically the same as hydrogen in that one electron orbits the nucleus, the compositions of their nuclei are different (see Figure 53). The basic hydrogen atom, the most abundant element in the universe, consists of a proton nucleus orbited by an electron. The deuterium (D) nucleus, on the other hand, contains a neutron and a proton. Deuterium accounts for 1 in every 7000 hydrogen atoms on earth and because it is found in all water represents an abundant and relatively inexpensive fuel. Canada has already produced many tonnes of deuterium in the form of heavy water (D_2O). Tritium (T), a third type of hydrogen, has two neutrons and a proton in its nucleus. The nucleus, however, is unstable, as one of its neutrons eventually disintegrates into a proton and electron. The electron is ejected from the nucleus as an energetic β particle. Tritium is, therefore, radioactive and has a half-life of 12 a.

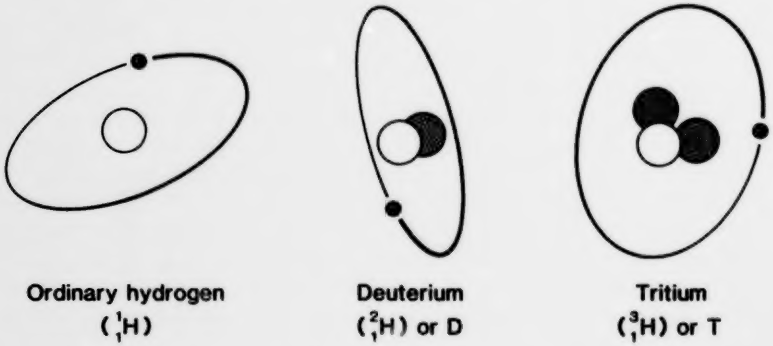


Figure 53 A comparison of hydrogen and its two isotopes, deuterium and tritium

Only a small number of fusion reactors, all highly experimental and none generating more energy than they consume, are operating today. They represent two completely different approaches to building fusion reactors: magnetic confinement and inertial confinement.

In magnetic confinement, hydrogen gas is heated until it reaches the plasma state in which atoms are stripped of their electrons. The result is a swirling cloud consisting of charged particles, the electrons and nuclei that used to constitute the atoms (see Figure 54).

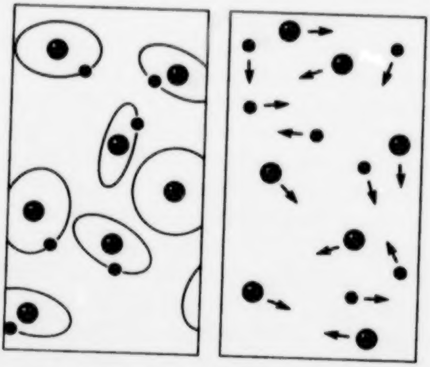


Figure 54 Complete atoms (left) and plasma (right)

Since no material can withstand a temperature of 100×10^{6} °C, the experimental magnetic confinement machines contain the plasma with a series of magnetic fields, a process that might be compared to holding a blob of jelly together with elastic bands. Although the charged plasma particles cannot readily move across the magnetic field, some particles will eventually diffuse through the restraining magnetic force field. This leakage is sufficient to cool the remaining plasma, hindering the burning of the isotope fuel. Finding leakproof ways to confine plasma is a major problem in fusion science.

To date, the Soviet Union has developed the most successful geometric approach for a magnetic confinement reactor. Called the tokamak (from the Russian words for "torus," "chamber," and "magnetic"), the Soviets revealed the basic design to the world in the late 1950s. By the late 1960s, experimental results indicated a major breakthrough; the difficult problem of plasma leakage was drastically reduced. Since then, several major tokamaks have been constructed in the United States, Japan, and Europe. The tokamak consists of a torus (a doughnut-shaped chamber) surrounded by magnetic field coils which produce strong magnetic fields that keep the plasma from touching the chamber walls and force it to move continually around the torus.

Before the end of the decade, it is expected that the scientific break-even point will be demonstrated in a tokamak reactor. This means that as much energy will be generated by the plasma as will have gone into producing it. To achieve this milestone will require maintaining the plasma at 100×10^6°C for about 1 s at a density of 10^{14} atomic particles per cubic centimetre (only three-millionths that of ordinary air). The confinement time can be shortened if the particle density is increased to produce the required number of nuclei collisions. This relation of confinement time to particle density, as a means of determining net energy gain, is known as the "Lawson Criterion."

A variety of methods can be used to fuel fusion reactors. A specialized gun can fire a frozen pellet of deuterium and tritium into the plasma. The pellet, on entering the plasma, would flash like a comet and be consumed in a fraction of a millisecond. Another fueling technique involves introducing puffs of deuterium–tritium gas into the plasma.

In a commercial fusion reactor, which is not expected to be constructed before early in the next century, the neutrons produced by the fusion of hydrogen isotopes will pass through the reactor's vacuum vessel walls (within whose boundaries the plasma is contained) and be absorbed in a surrounding "blanket" wall containing the light metal lithium. The resulting heat will be used to produce steam to drive a turbine and, as well, the neutrons will convert some of the lithium into tritium fuel.

An alternative to magnetic confinement fusion is inertial confinement, where there is no need to confine a large tenuous plasma inside a reactor. Instead, a powerful laser beam is focused on a deuterium–tritium fuel pellet for 1 ns. At the world's leading centre of inertial confinement fusion, the Lawrence Livermore Laboratories at the University of California, the Nova laser can generate, for an instant, 40×10^{12} W.

The basic concept of inertial confinement is to concentrate enormous energy on the deuterium–tritium fuel pellet in so short a time that the shock waves created by the explosion of the pellet's surface implode to a small point at the centre of the pellet. Laser energy is widely used in inertial fusion experiments, but intense beams of heavy or light ions are also being studied.

Whatever energy source is employed, the goal is to increase the density of the fuel pellet to 10 000 times the normal density of matter. As the pellet becomes denser its temperature rises and eventually surpasses the ignition point, 50×10^6°C. The fuel burns so quickly under these high densities that a detonation wave is formed in picoseconds, expanding outward from the centre.

In an instant, the pellet — smaller than a head of a pin — has been transformed into a fireball in the reactor cavity, releasing the energy equivalent of a few sticks of dynamite (each fusion reaction of a deuterium and tritium ion releases 17.6 × 10^6 eV. Since the pellet has little mass, however, it generates little explosive force. Dozens of pellets would be fed into the reactor every minute. Neutrons from the fusion reactions would be absorbed by the lithium blanket wall, producing heat and tritium.

Inertial confinement is neither as well understood theoretically nor as technically advanced at this stage as magnetic confinement. Part of the reason, aside from the fact it is a newer concept, is that the implosion process is difficult to study and monitor, occurring as it does within nanoseconds and a distance scale of about 1 μm.

Nuclear fusion is often described as the ultimate energy source. Eventually, it is hoped that deuterium, which is essentially inexhaustible and readily obtainable, will provide all the fuel for fusion reactors. Moreover, problems of handling of the fuel and disposal of radioactive materials, primarily parts of the reactor itself, would be minor compared to those associated with current fission reactors. The ash (helium) in the exhaust is not radioactive and any unburnt deuterium–tritium fuel would be extracted by vacuum pumps and recycled. There would be no risk of runaway reactions since the plasma is easily extinguished by any disturbance in the operating conditions. (In any event, only a very small amount of fuel, adequate to sustain a plasma for less than a minute, would be in the reactor at any given time.)

The current fusion reactors are experimental devices being used to establish the scientific feasibility of operating a large-scale fusion system. Considerable scientific data must be gleaned from their operation before the next stage in the evolution of fusion technology can occur — the construction of engineering test reactors sometime in the 1990s.

Program Rationale and Background

During the 1960s and 1970s nuclear fusion was a technological orphan in Canada, despite the significant commitments other nations were making to develop its potential. Canadian research related to fusion was carried out by a handful of researchers at NRC, the Institut de recherche d'Hydro-Québec (IREQ, the research arm of Hydro-Québec), and a small number of universities. Periodically, technical reports by concerned members of the scientific community urged the federal government to fund at least a small national program so that Canada could contribute to the scientific and technical development of fusion energy. The failure to contribute, the government was warned, could result in Canada being denied access to foreign know-how in fusion technology.

The National Research Council championed this view and after extensive consultation with Canada's fusion community, announced a fusion plan in 1978. No significant funding accompanied the announcement, however. The philosophy of NRC concerning fusion eventually formed the main features of the Canadian fusion program, which commenced in 1981, within the structure of the Panel on Energy Research and Development.

National Research Council Role in Fusion Energy Research

The long-term goal of the NRC's fusion energy program was thus to develop the base of science, technology, and engineering knowledge that will be necessary to implement fusion power systems, when they become economically viable. The shorter-term goal was to forge effective research linkages with other nations and international organizations sponsoring fusion research.

The National Research Council's fusion program was based on the premise that Canada had to contribute specialized knowledge in each of the three key areas of fusion research: magnetic confinement, inertial confinement, and materials/engineering. By developing world-class expertise in selected specialties, Canadian researchers could interact with fusion specialists from other nations, enabling this country's researchers to keep abreast of the major fusion energy developments and commercial opportunities abroad.

The magnetic confinement fusion sub-program helped fund a modest, but unique, scientific tokamak reactor at IREQ's research facility in Varennes, Quebec. The Tokamak de Varennes is managed by IREQ. The federal government's 1981 announcement that it would, through NRC, fund half the $40 million cost of building the tokamak launched the Canadian fusion program.

One year later, the second plank of the program was implemented, with the federal government providing 50% of the financing to assist Ontario Hydro and the Ontario Ministry of Energy in establishing a centre of expertise in tritium technology. This includes the purification, storage, and transportation of tritium, as well as the development of environmental monitoring and safety standards. The Canadian Fusion Fuels Technology Project is managed by Ontario Hydro, on behalf of the funding partners.

The inertial confinement part of the fusion program still awaits implementation. Various groups in British Columbia, Alberta, and Quebec have worked with NRC to establish a specialized program in inertial confinement that might be co-funded with the federal government. However, no firm agreement has yet been made.

Potentially, the inertial confinement program, as outlined in an extensive NRC study, could lead to industrial spinoffs in high-powered pulsed gas lasers. Canadian researchers have traditionally been world leaders in designing such lasers and other optically based instruments, as aids in studying the interaction of laser beams and plasma. National Research Council research, for instance, played an instrumental role in helping Lumonics Inc., now one of the world's largest manufacturers of lasers, develop new products.

Research in inertial confinement continues at NRC and three Canadian universities: University of British Columbia, University of Alberta, and the University of Quebec's Institut national de la recherche scientifique – Énergie.

The Canadian fusion energy program has an annual budget of about $20 million, of which about half is funded by provincial utilities and other collaborators, and the remainder by the federal government.

International Status of Fusion Energy Research

Leading Countries and Performers

Worldwide spending on fusion research and development is $2 billion annually, with the United States, Japan, the European Economic Community, and Soviet Union each supporting programs with yearly budgets of about $500 million. Fusion research is the single largest non-military research project in the United States, Europe, and Japan.

The current centerpiece for all four of the major fusion energy programs is an advanced tokamak reactor, each costing about $500 million to build. The American Tokamak Fusion Test Reactor (TFTR) at Princeton University was the first to start operating, in 1982. Next to come on-line, in 1983, was the Joint European Torus (JET) located in Britain. Japan's machine, the JT-60, was completed in 1985. The Soviet Union's T-15, which has superconducting magnets that will allow long operating times, is scheduled to be activated in 1987. In addition to these large experimental fusion reactors there are a number of intermediate tokamaks, such as France's Tora Supra, Germany's TEXTOR, and Doublet III-D in the United States, plus dozens of smaller machines. Many experimental, non-tokamak devices, capable of producing plasma, are used to do research on plasma confinement.

To date, none of the major tokamaks has actually attempted to burn deuterium–tritium fuel. The reason is that burning tritium produces neutrons which would contaminate the reactor vessel and greatly complicate its future use. Heating just the deuterium at a high temperature produces many of the conditions that would occur in burning deuterium–tritium fuel.

Research Agreements and Collaboration

Canada participated in two of the International Energy Agency's fusion energy agreements. It joined the German-managed TEXTOR project, which analyzes plasma/wall interactions, as an initial step in international cooperation. Canadian research specialists made a number of important contributions to this program, three of which are considered especially significant.

The Canadian-developed data acquisition and control system provided detectors with sufficient "intelligence" to process data locally. The processed results are then forwarded to a large computer, which greatly accelerates data acquisition. The system performs diagnostic functions and can execute its tasks if the large computer is not operating or is otherwise occupied.

Another significant innovation, a laser-based CO_2 forward-scattering diagnostic, identifies peculiar types of plasma turbulence. The laser-based device is leading to fundamental new knowledge about plasma turbulence inside a reactor and is stimulating theoretical work. Its performance has exceeded expectations and now plays a vital role in TEXTOR experiments.

The final noteworthy development, done in conjunction with Germany, is the passive tritium pump for which a patent is pending. This pump, which consists of two metallic layers, is now at the demonstration phase. The pumping action is due to the fact that, in such metal bonds, tritium permeates preferentially in one direction. The advantage of this design is that it lacks moving parts and is completely leak tight because of its welded construction. For a particular range of pressures and tritium concentrations, the pump's reliability is ideal.

From a Canadian point of view, TEXTOR also provided another great benefit — experience in operating a device similar to the Tokamak de Varennes. Some of the equipment developed for TEXTOR will, in fact, also operate on the Varennes machine.

The second IEA agreement, radiation damage in fusion materials, did not focus on a single facility such as TEXTOR. Construction of a Fusion Materials Irradiation Test Facility (FMIT) in the United States was proposed but has been indefinitely delayed. The facility was to investigate neutron damage done to materials, the intention being to develop a materials database. Activities under this agreement are now being conducted in existing facilities in a number of countries.

Atomic Energy of Canada Limited is participating in discussions to develop a coherent radiation-damage program for the western nations and has conducted irradiation measurements at its research and development laboratories in Chalk River, Ontario.

Besides the IEA collaboration, Canada also negotiated separate bilateral agreements with other nations. One agreement with Japan, which may lead to further more extensive cooperation covers such fields as tritium technology and tokamak physics. The Japanese have provided AECL with lithium oxide crystals, which are difficult to obtain. These crystals could form the ceramic materials for constructing breeder blankets for fusion reactors. The other agreement, dealing with laser fusion, envisages building cooperative links with the Institute of Laser Engineering in Osaka, Japan, one of the world's major centres.

An agreement negotiated with the European Community's Euratom in 1983, but only formally signed in 1986, establishes a joint committee that can "fast track" smaller collaborative projects. This agreement has also already allowed Canadian scientists to work with various fusion reactors in Europe. As part of this program, more than a half-dozen scientists are assisting European projects; for example, two scientists are contributing to the design of the Next European Torus (NET), the engineering test reactor that will follow the Joint European Torus.

Potentially, the most significant bilateral agreement is being negotiated with the United States. Under negotiation for a number of years now, this agreement could result in the Canadian fusion research program being integrated with the American program. The technical details have been agreed on, but issues regarding intellectual property rights, disclosure to third parties, and other legal and administrative matters are not yet fully resolved.

Finally, Canada is participating in the Reagan–Gorbachev Inititative which seeks to encourage East–West cooperation in constructing a $2 to $4 billion engineering test fusion reactor. Canada's invitation to participate in this program is considered a major achievement for a nation having a modestly funded fusion research program (but considerable expertise in tritium technology). Japan and the European Community will be the other participants.

The Status of Fusion Research in Canada

Decades will pass before fusion energy becomes an economic reality, but in the meantime some commercial spinoffs, notably in the sale of tritium handling technology, fusion fuels, and sophisticated instrumentation, can be expected for Canadian industry.

The Tokamak de Varennes

International fusion energy experts were asked for their advice on the design of the Tokamak de Varennes. As a result, it has a number of innovative features that will enable unique experiments to be undertaken. While this particular tokamak cannot be considered a true fusion reactor (plasma temperatures will approach only 10×10^{6} °C, or one tenth what is needed to produce fusion reactions), it is designed to provide valuable scientific data about the interaction of plasma with reactor walls and other materials.

The reactor consists of several main components. Sixteen toroidal field coils surround the vacuum vessel system to produce the powerful doughnut-shaped magnetic field that serves as the primary means of confining the plasma in the middle of the vacuum vessel (see Figure 55). The magnetic coils of the Tokamak de Varennes are water cooled and thus can be pulsed for 30 s, compared to a second or less for many existing machines. This will enable researchers to undertake experiments yielding new data on the behaviour of "steady state" plasma in a tokamak. Such scientific data will be needed to deal effectively with the engineering-related problems involved in constructing larger-scale demonstration fusion reactors.

Eight ohmic heating coils produce a voltage around the torus and induce a current inside the plasma (see Figure 56). The plasma is heated by its resistance to this electrical current. This current is parallel to the magnetic field that confines the plasma.

The equilibrium field (EF) produced by two circular field coils helps keep the plasma in the middle of the vacuum vessel. The equilibrium field coils respond to sensitive detectors that are constantly monitoring the position of the plasma inside the reactor's vacuum vessel. (The ohmic and equilibrium coils are also called poloidal field coils.)

These three-coil systems are common to all tokamaks, but the Tokamak de Varennes contains two others not usually found on such machines. They form part of the vacuum vessel system. The divertor field coils (DF), also called magnetic limiters, guide the outer layer of plasma to a "divertor" plate. The divertor field coils allow an additional sophisticated control over plasma/wall interaction and enable a more versatile research program to be undertaken in studying this interaction.

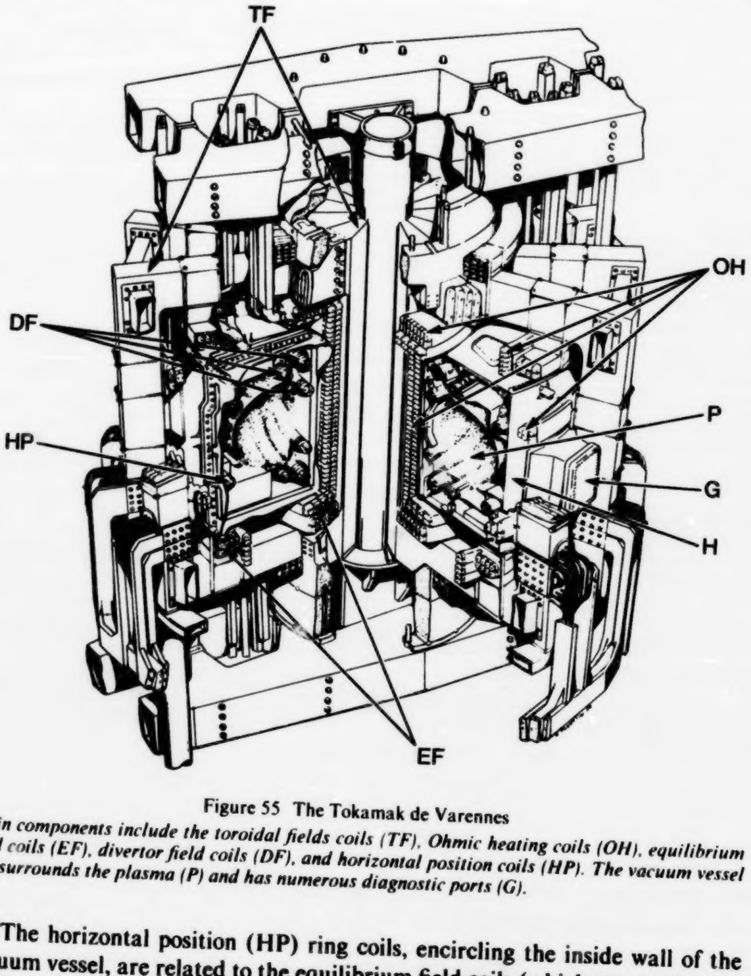


Figure 55 The Tokamak de Varennes

Main components include the toroidal fields coils (TF), Ohmic heating coils (OH), equilibrium field coils (EF), divertor field coils (DF), and horizontal position coils (HP). The vacuum vessel (H) surrounds the plasma (P) and has numerous diagnostic ports (G).

The horizontal position (HP) ring coils, encircling the inside wall of the vacuum vessel, are related to the equilibrium field coils (which are outside the vacuum vessel) and assist in preventing the plasma from drifting into the vessel wall. Although this set of internal coils does not generate a large magnetic field for controlling the plasma, it reacts to changes in the plasma's position 10 times faster than the much more powerful equilibrium field. (The reason for the equilibrium field's slower reaction is that it must penetrate the conducting wall of the vacuum vessel.) The horizontal position coils remain

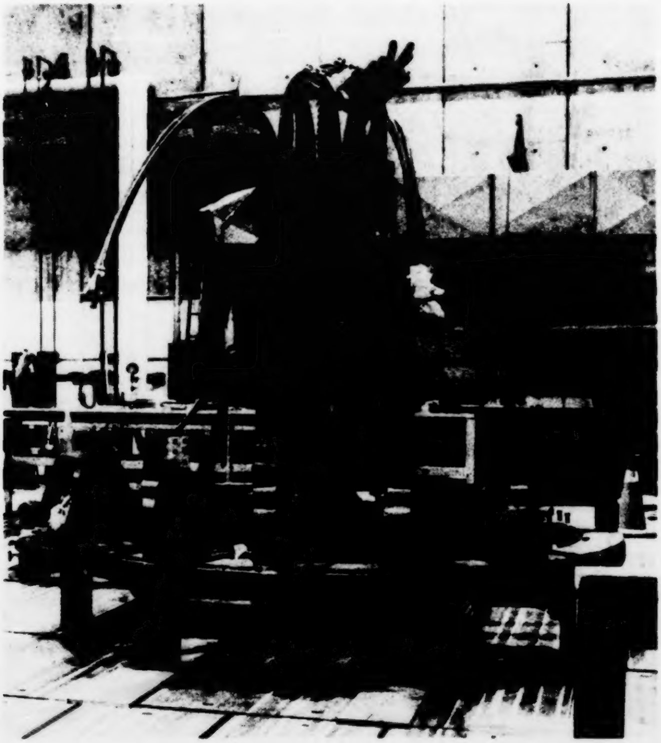


Figure 56 The central solenoid coil of the Tokamak de Varennes Ohmic heating coil system

activated until the equilibrium field assumes control (a computer coordinates the operation of the two fields). The horizontal position coils represent an advanced means of controlling the plasma and their reaction speed will permit researchers to perform experiments aimed at observing certain types of plasma phenomena early in their development. (The divertor and horizontal field coils are also referred to as internal poloidal field coils.)

The stainless steel vacuum vessel, where the plasma is created and confined, has a rectangular cross-section and a doughnut shape (see Figure 57). It is designed to accommodate removable liners, which shield the rest of the vacuum vessel system from plasma radiation. The liners are made from a

Figure 57 The vacuum vessel of the Tokamak de Varennes with the lid about to be put in place

variety of metals, including steel and molybdenum. The choice of liners is an important consideration for those doing experiments on plasma/wall interactions, since liners release impurities into the plasma. Researchers, for example, may not want iron atoms in the plasma and would select a liner with that factor in mind.

The vacuum vessel is equipped with numerous diagnostic ports. Researchers will use them to investigate the ultraviolet light, X-rays, infrared light, neutrons, and magnetic oscillations emitted by the plasma. The ports will also allow the extraction of various particles ejected by the plasma; greater knowledge of these particles will reveal much about the nature of the plasma itself.

To start a tokamak such as the one at Varennes, the toroidal field is turned on first and then the ohmic and equilibrium fields are activated almost simultaneously. The power supply driving the ohmic heating coils of the tokamak at Varennes is designed to produce, initially, a high voltage, which ionizes a gas (usually hydrogen) to form low-temperature plasma. As the current is increased from 1000 A to more than 200 000 A, the temperature of the plasma also increases. Since plasma is a good electrical conductor, the required voltage drops as current strength increases (from hundreds of volts initially to 1 V during the last several seconds of the reactor's operation).

The Tokamak de Varennes was designed by a consortium, headed by IREQ, which included Canatom Inc., Canada's largest nuclear engineering consulting company, MPB Technologies Inc., a Montreal-based instrumentation company, University of Quebec's INRS – Énergie, and the University of Montreal.

A number of electronic devices have already been developed for the Tokamak de Varennes, scheduled to produce its first plasma in late 1986. One of these devices is the ultraviolet matrix detector, developed by MPB Technologies and INRS – Énergie. Its speed of operation is unique and it can perform, within a millisecond, 1000 measurements of ultraviolet radiation from a tokamak plasma. The purpose of the detector is to measure the interaction of contaminating wall materials with the plasma. The detector is coupled to a spectrometer, which identifies elements by the wavelengths they emit.

The Tokamak of Varennes is providing Canada's advanced technology industry with a small and important market. RCA Laboratories in Montreal, for instance, developed avalanche photodiodes to measure light signals having a very short wavelength. The photodiodes, the most sensitive in the world for detecting such light signals, are part of a system that measures the amount of laser light scattered by plasma, as well as its shift in frequency. By gathering this data, it is possible to deduce the temperature and charged particle densities of the plasma.

Canadian Fusion Fuels Technology Project

Over the next 20 years Canada could become a major supplier of tritium fuel for scientific and engineering test fusion reactors. Tritium is a contaminant of the heavy water moderator in CANDU fission reactors and consequently AECL and Ontario Hydro have developed considerable expertise in dealing with the substance.

The Canadian Fusion Fuels Technology Project (CFFTP) is funded by the federal government (50%), Ontario Hydro (25%), and the Ontario Ministry of Energy (25%). (In a separate activity, Ontario Hydro plans to start operating its Tritium Removal Facility in 1987. During the next 20 years, it is expected that this facility will extract close to 50 kg of pure tritium which currently is valued at $15 million/kg).

The Canadian Fusion Fuels Technology Project's expertise in managing tritium is respected throughout the world. It is supporting research regarding the manner in which tritium interacts with the environment, runs a training course for the world's fusion community on tritium safety, and markets engineering and related services abroad.

The Project's technical and financial support assisted Scintrex Ltd. of Concord, Ontario, to develop a tritium-in-air monitor which is recording market success. Other companies are actively participating in the R&D program of the Canadian Fusion Fuels Technology Project, notably Spar Aerospace Ltd. and CAE Electronics Ltd. (in remote handling systems).

Through the Canadian Fusion Fuels Technology Project, Canada is also supporting programs to develop breeder blankets at AECL's main research laboratories at Chalk River. In conjunction with Grumman Aerospace of New York and Rensselaer Polytechnical Institute, AECL is promoting the concept of an aqueous lithium salt solution as the breeding blanket for Europe's next generation fusion reactor, Next European Torus. Although its ability to breed tritium is only marginal, it has the merit of being low-cost and much less of a technical risk than regular breeding blanket technology. Machines like the Next European Torus, of course, will be used for engineering studies and not for generating electricity (where tritium production would be a major concern), so the concept of a less expensive and technically less demanding breeder blanket for an engineering machine is gaining acceptance in Europe and the United States.

Atomic Energy of Canada Limited is also developing solid breeder blankets. The fusion of hydrogen isotopes aside, the development of breeder blankets is the most technically taxing task associated with the development of larger reactors. The breeder blanket will convert lithium into tritium fuel, as well as produce heat for the production of steam; it will have to resist material damage caused by a neutron flux that is far greater than anything associated with nuclear fission reactors.

Researchers at AECL are testing lithium aluminate ceramics as a material for constructing breeder blankets. The lithium is part of a lithium–aluminum–oxygen molecule. In a reactor, the neutrons released by the fusion of hydrogen isotopes would be captured by the lithium in the ceramic and converted into tritium gas. This gas would be released through the pores in the ceramic material and collected as a reactor fuel.

Recommendations

Regarding nuclear fusion energy research, it is recommended that:

1. The close collaboration between government, electrical utility, industry, and university laboratories within Canada should continue and also be enhanced.
2. Canada's fusion strategy should continue featuring international collaboration to strengthen the mainstream activities of the world's leading fusion nations and provide domestic awareness of these major international programs.
3. Tritium technology should continue to be broadly developed to open fuel handling and supply opportunities in the international fusion research community.
4. Strong efforts should be made to develop and exploit the special features of the Tokamak de Varennes internationally, in particular its long-pulse capability and the research team's expertise in instrumentation.
5. A program to develop high-powered pulsed gas lasers should be undertaken in collaboration with industry, thus maintaining Canadian expertise and awareness in inertial confinement fusion, as well as creating new commercial opportunities in an advanced field of technology.

EPILOGUE

As this report has demonstrated, many technical milestones have been achieved by those performing research and development into alternative energy technologies in Canada during the past dozen or so years.

The contribution from alternative energy has more than doubled between 1974 and 1984 and now supplies the equivalent of almost 6% of domestic energy consumption. However, perhaps the most significant contribution of alternative energy research and development is the potential resiliency it has injected into the Canadian energy system, which until very recently was predominantly reliant on oil. Should another energy crisis occur, viable energy alternatives could be deployed in a reasonably short time and from a sound technical base.

Although an energy crisis might now seem remote to many Canadians, this report concludes with a brief consideration of the future of alternative energy, given three possible energy scenarios:

- a sudden increase in international oil prices
- a widespread, international, public reaction against energy from nuclear fission
- progressive deterioration of the atmospheric environment due to the production of acid precipitation and carbon dioxide

The first scenario could be brought about by political or military disruption among international oil suppliers or by a major escalation in demand for oil in other parts of the world. In effect, this would be a replay of the 1973 oil shock and would particularly impact the price and availability of transportation fuels. But there would be one important difference: more than a decade of research in Canada and abroad should permit a rapid introduction of alcohol fuels or other synthetic fuels produced from natural gas or biomass.

Every link in the biomass liquid fuel chain has been considerably strengthened during the past 13 years, from the development of equipment for harvesting and processing specially bred trees capable of rapid growth, to the conversion of this wood into synthesis gas and then into methanol. Engines designed to burn alcohol fuels have also been technically refined. Alcohol fuels would be more expensive than hydrocarbon fuels, but their availability could help avert a major transportation crisis. To a lesser extent, an oil shortage would also rekindle interest in solar energy, especially for space and water heating in industrial and commercial buildings.

A different type of energy crisis would result from a strong international backlash against nuclear fission reactors, possibly brought on by a serious malfunction of a nuclear power plant somewhere in the developed world. Such an incident could bring to a halt the construction of any new nuclear power plants in the western world and possibly accelerate the closure of some operating plants. Canadian authorities would, with others, come under extreme pressure to abandon electrical generation by nuclear fission reactors, notwithstanding the excellence of the Canadian nuclear power systems. If this were to happen, electricity prices would increase very rapidly. Energy conserving devices like heat pumps would be in heavy demand and a dramatic shift away from electric heating could be expected. Alternative generation from wind turbines would play an important role and could have significant impact in the Atlantic provinces. Interest would resume in solar heating systems, as it would in buildings incorporating passive solar features in their basic design. Smaller power plants, fueled by wood and peat, would be constructed and rapidly put into service. Additionally, the abandonment of nuclear fission reactors could encourage the accelerated development of commercial fusion reactors. They are inherently more safe since only a very small amount of radioactive gas could be released in even a major failure of the reactor.

Finally, a third type of energy crisis could occur if continuing production of acid rain and carbon dioxide were to cause large-scale damage to the environment or to change the climate drastically. Acid rain is already destroying aquatic life in many lakes in North America and Europe and may seriously decrease productivity of forests and agricultural lands in the future. Moreover, the further buildup of carbon dioxide from the burning of fossil fuels could eventually raise the average annual temperature of the atmosphere significantly, causing major disturbances to global weather patterns and ocean levels. Although this is decidedly a long-term problem, it represents the most threatening challenge to the continued expansion of energy use and will require global action to correct. Conventional hydrocarbon fuels and coal would have to be greatly curtailed in their use, since they all add carbon to the atmosphere. Solar and wind energy would become extremely important, as would nuclear-generated electricity. Electricity would be used to produce hydrogen or liquid hydrogen carriers as transportation fuels, in addition to seeing expanded conventional uses.

It may be that the future energy crisis, when it emerges, will not neatly fit any of the three scenarios described above, or perhaps it may be some combination of the three. The scenarios can, however, be used like the oversimplified models that engineers construct to glean insights about complex systems. One inescapable conclusion that must be drawn about alternative energy technologies is that they represent insurance against drastic disruptions in our energy system.

What seems to be required during the short term is an appropriate continuing research program aimed at enhancement of the promising alternative energy technologies through, for example, the incorporation of improved materials and analytical design tools. This will also have the benefit of sustaining a core of scientific and engineering expertise. Then, as the need arises, informed scientists and engineers will be available to help direct the efficient and timely implementation of appropriate energy technologies.

APPENDIX: ABBREVIATIONS AND UNITS

Abbreviations

A	ampere
a	year
AECL	Atomic Energy of Canada Limited
BCTIS	Biomass Conversion Technical Information Service
C	coulomb
°C	degree Celsius
CECE	combined electrolysis and catalytic exchange
CFFTP	Canadian Fusion Fuels Technology Project
CIDA	Canadian International Development Agency
CHIP	Canadian Home Insulation Program
CIPH	commercial and industrial process heating
cm	centimetre
COP	coefficient of performance
COSP	Canadian Oil Substitution Program
d	day
DBR	Division of Building Research
DFFR	downflow fixed film reactor
DHWS	domestic hot water system
DME	Division of Mechanical Engineering
ECSI	Experts-Conseils Shawinigan Inc.
EEC	European Economic Community
EJ	exajoule
EMR	Department of Energy, Mines and Resources
ENFOR	Energy from the Forest
eV	electronvolt
FIRE	Forest Industry Renewable Energy
FMIT	fusion materials irradiation test

ft	foot
g	gram
gal	gallon
GJ	gigajoule
GWh	gigawatt-hour
h	hour
HAWT	horizontal-axis wind turbine
IDRC	International Development Research Centre
IEA	International Energy Agency
INRS	Institut national de la recherche scientifique
IPS	International Peat Society
IRC	Institute for Research in Construction
IREQ	Institut de recherche d'Hydro-Québec
J	joule
JET	Joint European Torus
kcal	kilocalorie
kg	kilogram
km	kilometre
kW	kilowatt
kWh	kilowatt-hour
L	litre
m	metre
MHz	megahertz
min	minute
mm	millimetre
MPa	megapascal
mV	millivolt
MW	megawatt
MWh	megawatt-hour
NEP	National Energy Program
NET	Next European Torus
NRC	National Research Council of Canada
ns	nanosecond
NSERC	Natural Sciences and Engineering Research Council
NSTF	National Solar Test Facility
OECD	Organization for Economic Cooperation and Development
OERD	Office of Energy Research and Development
ORF	Ontario Research Foundation
PASEM	Program of Assistance to Solar Equipment Manufacturers
PERD	Panel on Energy Research and Development

PJ	petajoule
ppm	parts per million
PUSH	Purchase and Use of Solar Heating
RD&D	research, development and demonstration
rpm	revolutions per minute
R&D	research and development
s	second
SEDP	Solar Energy Development Program
SRF	short-rotation forestry
t	tonne
TFTR	Tokamak Fusion Test Reactor
V	volt
VAWT	vertical-axis wind turbine
W	watt
WECS	wind energy conversion system
Wh	watt-hour
μm	micrometre

International System of Units

The international System of Units is founded on the base units listed in Table A1.

Table A1. SI base units

	Unit	Symbol
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd
Supplementary units are		
Plane angle	radian	rad
Solid angle	steradian	sr

Derived units are formed algebraically in terms of base units and/or supplementary units. Table A2 gives some derived units.

Table A2. Some derived units

	Unit	Symbol
Energy, work, quantity of heat	joule	J
Power	watt	W
Temperature	degree Celsius	°C
Pressure	pascal	Pa
Frequency	hertz	Hz
Electric potential, potential difference, electromotive force	volt	V
Quantity of electricity, electric charge	coulomb	C

The SI prefixes given in Table A3 are used to form names and symbols of decimal multiples and sub-multiples of SI units.

Table A4 gives other units permitted for use with SI.

Table A3. Standardized SI prefixes

Power	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

Table A4. Units permitted for use with SI

	Unit	Symbol
Time	year	a
	hour	h
	day	d
	minute	min
Energy	electronvolt	eV
Mass	tonne	t
Volume	litre	L

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